



International Energy Agency IEA Implementing Agreement on District Heating and Cooling, including the integration of CHP

## DYNAMIC HEAT STORAGE OPTIMISATION AND DEMAND SIDE MANAGEMENT



Fraunhofer Institut Umwelt-, Sicherheits-, Energietechnik UMSICHT



IEA R&D Programme on District Heating and Cooling

# Dynamic Heat Storage Optimisation and Demand Side Management

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#### Introduction

The International Energy Agency (IEA) was established in 1974 in order to strengthen the cooperation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

The IEA's *World Energy Outlook*<sup>1</sup> "Reference Scenario" 2004 projects that, in the absence of new government policies or accelerated deployment of new technologies, world primary energy demand will rise by 59% by 2030, with 85% of that increase from the use of coal, oil and natural gas. However, these trends are not unalterable. The *World Energy Outlook* "Alternative Policy Scenario" shows that more vigorous government action and accelerated deployment of new technologies could steer the world onto a markedly different energy path, where world energy demand would be 10% lower and carbon-dioxide emissions 16% lower. *DHC makes a difference* 

One of the key technologies that can make a difference is District Heating and Cooling.

DHC is an integrative technology that **can** make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating **and** cooling. The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based airconditioning, rapidly growing in many countries, can be displaced.

As an element of the International Energy Agency Programme, the participating countries undertake co-operative actions in energy research, development and demonstration.

One of the programmes that has run for more than 25 years is the Implementing Agreement 'District Heating and Cooling including the integration of Combined Heat and Power'.

Annex VII

In May 2002 Annex VII started.

Following is a list of the recent research projects (annexes) undertaken by the District Heating & Cooling Implementing Agreement. Ten countries participated from Europe, North America and Asia: Canada, Denmark, Finland, Germany, Korea, The Netherlands, Norway, Sweden, United Kingdom, United States.

<sup>&</sup>lt;sup>1</sup> The annual *World Energy Outlook* presents long-term projections for supply and demand of oil, gas, coal, renewable energy sources, nuclear power and electricity. It also assesses energy-related carbon dioxide emissions and policies designed to reduce them. The annual World Energy Outlook has long been recognized as the authoritative source for global long-term energy market analysis. This flagship publication from the IEA is produced by the agency's Economic Analysis Division with input from other internal and external energy experts as required. For more information see http://www.worldenergyoutlook.org/.

| Project title   | Company  |                |
|---|--|----------------|
| A comparison of distributed<br>CHP/DH with large-scale<br>CHP/DH  | Parsons Brinckerhoff Ltd<br>Formerly PB Power Ltd – Energy<br>Project leader:<br>Paul Woods            | 8DHC-<br>05.01 |
|   |  |                |
| Two-step decision and<br>optimisation model for<br>centralised or decentralised<br>thermal storage in DH&C                          | SP Swedish National Testing and<br>Research Institute<br>Project Leader:<br>John Rune Nielsen          | 8DHC-<br>05.02 |
|   |  |                |
| Improvement of operational<br>temperature differences in<br>district heating systems  | ZW Energiteknik<br>Project leader:<br>Heimo Zinko  | 8DHC-<br>05.03 |
|   |  |                |
| How cellular gases influence<br>insulation properties of district<br>heating pipes and the<br>competitiveness of district<br>energy | Danish Technological Institute<br>Project leader:<br>Henning D. Smidt                                  | 8DHC-<br>05.04 |
|   |  |                |
| Biofouling and<br>microbiologically influenced<br>corrosion in district heating<br>networks   | Danish Technological Institute<br>Project Leader:<br>Bo Højris Olesen                                  | 8DHC-<br>05.05 |
|   |  |                |
|   |  | opuc           |
| Dynamic heat storage<br>optimization and Demand Side<br>Management  | Fraunhofer Institut Umwelt-, Sicherheits-,<br>Energietechnik UMSICHT<br>Projectleader: Michael Wigbels | 8DHC-<br>05.06 |
|   |  | ODUC           |
| Strategies to manage heat<br>losses – Technique and<br>Economy  | Innovationsmanagement<br>Project leader: Frieder Schmitt   | 8DHC-<br>05.07 |
|   |  |                |

#### Benefits of membership

Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

- DHC is already a mature industry
- DHC is well established but refurbishment is a key issue
- DHC is not well established.

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include the cross-fertilisation of ideas which has resulted not only in shared knowledge but also opportunities for further collaboration.

New member countries are very welcome - please simply contact us (see below) to discuss.

#### Information

General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website <u>www.iea-dhc.org</u> or from:

| The Operating Agent                    | IEA Secretariat                          |  |  |
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### **Project Organisation**

This work has been organised in the following way

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Seven Technologies, Denmark for co-operation on the Termis simulation programme installed in Næstved DH company.

Ms. Marijke Wobben, NOVEM.

In a partnership of the Department of Mechanical Engineering, Technical University of Denmark, the Finnish Research Institute VTT Processes and the German Fraunhofer Institute for Environmental, Safety und Energy Engineering UMSICHT within this project heat storage possibilities in the respective partner countries have been evaluated. For this purpose three different district heating systems in the participating IEA member countries have been regarded. On basis of different strategies to determine the possible impact of heat storage applications in district heating systems the economic and ecological effects for energy supply companies supplying heat and electricity can be estimated. Within this context especially heat storage applications with respect to the storage capacity of the pipeline system of the district heating network were regarded. Additionally, demand side management strategies based on a partial reduced supply of several customer substations in order to apply the building's volume and mass as a heat storage were in the centre of interest. These Dynamic Heat Storage (DHS) and Demand Side Management (DSM) strategies can be used as a supplement to steel tanks or other ways of heat accumulation.

The investigations were based on a state of the art report identifying the mathematical strategies available to determine the heat storage capacity of the district heating network and the possibilities to improve the operation of the district heating system by demand side management. In this context existing simulation tools, optimisation strategies and necessary algorithms to simplify the network complexity have been presented.

Regarding the complexity of district heating networks and the models describing the characteristics of these systems it was necessary to simplify the model structure. Only this step enabled an effective simulation and optimisation in order to determine possible improvements of dynamic heat storage in the network system. For this purpose at the Technical University of Denmark and at the German Fraunhofer Institute UMSICHT different mathematical approaches have been developed during the last years. These "network aggregation" strategies were described and compared in order to determine differences towards the level of accuracy of the simplified network model compared to the detailed model. Although the methods are based on different algorithms it has been shown that both approaches allow a high accuracy between the detailed and the aggregated model.

A major step in this project was the collection of structural and measurement data of the involved energy supply companies. Therefore, over a wide horizon of the project's duration data has been collected. These information were used for the modelling sequence of the project. In all partner countries measurements were carried out at various points in the district heating network. This characteristical network data has been collected in each case for representative seasons of the year, namely the summer, the winter and the intermediate season in order to provide a reliable data basis for further investigations.

After the state of the art of dynamic heat storage (DHS) and demand side management (DSM) had been determined and a sufficient data basis was available the project group started the evaluation sequence of this project. As first the district heating networks of the involved energy supply companies were aggregated to a level which enables the following simulation and optimisation calculations. For this purpose it was preliminary necessary to elaborate detailed models of the Danish district heating system of the city Næstved, the German DH-system of Oberhausen and the Finnish Jyväskylä system. Within this context it has been determined that a good model of the system can be elaborated based on measurement data of the largest customers in the DH-system.

Within this step of the project it has been established that model based simulation and optimisation can be carried out with meaningful results on the precondition that reliable data is available. To carry out the complex simulations and optimisations in most cases an aggregation of the DH network was necessary.

Based on the detailed structure of the mentioned networks and steady state simulation results it was possible to simplify the structure of the networks significantly. All systems have been aggregated to a level of 10 % to 20 % of the original complexity without loosing the main characteristics of the systems.

In a next step the project group applied available strategies in order to determine the operational improvement of the involved energy supply systems by DHS and DSM strategies. The dynamic heat storage evaluations were based on simulation and optimisation calculations using the aggregated network models. Most calculations to estimate the improvement due to demand side management were based on the demand side management model developed at VTT. In order to determine the maximum impact in the operational optimisation, DHS and DSM should be utilised as much as possible.

In the Næstved case it has been shown how DHS could be used to store heat in the network if a failure in the CHP/waste incineration plant occurs. For the Parkvej subsystem in Næstved it has been shown how DHS can be used to avoid the use of expensive fuel during the morning peaks. Simulations showed that DSM can further help not to use the expensive fuel at peak loads.

Within model based calculations on the Jyväskylä DH-system it has been determined that the maximum heat input for shaving of the morning peak is about 20 MW and in total 42.5 MWh can be stored in the network on the morning of 130 days. In total there is a dynamic heat storage potential of 5400 MWh for cutting the peak loads in the morning over a period of up to 4 hours. The total cost savings were about almost 100000 US\$ per year and heavy oil was saved in a range of 510 t/a. Since in this case the peak load oil production was substituted by heat production from peat the CO2-Emission increased by 741  $t_{CO2}/a$ .

Within the EVO case it has been evaluated whether the uncoupling of heat and power production in a CHP system could lead to financial and economic advantages. In average additionally 41 MWh power could be produced per day during peak times and sold with profit. This additional power production enables savings of up to 55000 US\$ for the heat storage in the supply line and the return line.

What concerns the economic impact of demand side management the following results have been obtained due to model based calculations of the Jyväsylä system. Based on simulations how to use energy production capacity when DSM is utilised, the total direct saving are 17000 US\$/a in the Jyväskylä case. If we assume to save an investment of a 20 MW HOB because of DSM, additional savings of 187000 US\$/a are possible. When using DSM in Jyväskylä the emission reduction of  $CO_2$  was 84 t/a.

Within this context it should be pointed out, that dynamic heat storage in the pipeline system could be carried out without any investment costs. The additional heat losses due to higher supply temperatures are comparable small. However, it could influence the lifetime of pipes and compensators. Therefore, the temperature gradient during the initiation of the loading procedure should be quite low. DSM can also be utilised in the planning of future production capacity.

All results can be summarised as follows:

- For DH systems with electricity production (CHP), DHS will increase the possibility for electricity production, resulting in economic savings of up to 2 % per day determined in the Jyväskyla and EVO cases. For the entirely Finish DH market savings can be estimated of about 3 million US\$ a year.
- For DH systems without electricity production, the savings will be smaller, but DHS can be used to store heat made from the cheapest fuel source, for instance if a failure in the supply occurs as it has been simulated for the Næstved system.
- DSM should be used to cut peak loads in order to shift from expensive to cheaper fuel.
   Possible savings of approximately 1-2% in Jyväskyla and Næstved have been determined.
   For the Finnish DH market due to DSM savings of about 6.5 million US\$ a year are possible.

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### 1. Introduction

Within the finished IEA Annex VI project "Simple Models for Operational Optimisation" data from real DH-systems in Denmark, Finland and Germany have been used to study the effects of different simplification strategies on the accuracy of DH network models for simulation and optimisation purposes. The application of these algorithms was very promising.

As a continuation the project "Dynamic Heat Storage Optimisation and Demand Side Management" has focused on the application of the developed and tested simplification strategies in order to evaluate advantages of dynamic heat storage (DHS) optimisation techniques for the Finnish DH system of the city Jyväskylä and the Danish DH system of Næstved . Additionally, for these systems demand side management (DSM) strategies will be evaluated and compared to the effects of dynamic heat storage applications.

As a result of the analysis, a basis for recommendations towards energy suppliers, DH companies, decision-makers etc. have been established which allow the evaluation of economic savings by dynamic heat storage processes in the pipeline system at specific supply situations. Furthermore economic savings and reductions in  $CO_2$  and peak demands in the connected gas and electricity systems have bee regarded by reducing peak loads in the connected buildings (DSM) and at the DH plants.

Three different energy supply systems in Denmark, Finland and Germany which are typical for most countries participating in the Annex VII Implementing Agreement have been regarded and corresponding data has been collected and exchanged between the partner countries.

These investigations should not only support operating and management processes in companies of the participating countries but also have a relevance for companies working with comparable energy supply strategies in other countries.

### 2. State of the Art

#### 2.1. Simulation Tools for DH Systems

Real DH-systems are very complex since they consist of many elements like pipes and consumers. The corresponding models especially regarding dynamic purposes are also very detailed what leads to high computation times. To enable complex optimisation strategies usually the systems have to be simplified or aggregated. These aggregation strategies are mostly based on results processed by either steady state or dynamic calculations.

In the following text different simulation tools are described which are used in district heating companies or research facilities in Germany, Finland or Denmark.

#### 2.1.1. Steady State Simulation

A number of commercial simulation tools are available in Denmark, Germany and Finland for simulation of DH systems, either developed and supported by consulting engineers, research institutes or by special software companies. Some programmes can only carry out steady state simulations, like the Danish District Heating Association's programme, CONDOR by Carl Bro a/s, the German simulation systems EcNetz (FrieTech Software GmbH) or RNET (Lauterbach Verfahrenstechnik) which is designed for hydraulic calculations.

#### 2.1.2. Dynamic Simulation

Tools like SYSTEM RORNET (Ramboll), Termis (Seven Technologies) and BoFiT (ProCom) can in addition do transient simulations of both fluid flow and thermal response. In addition to these programmes, the universities have developed programmes, which in general are not user friendly, or supported. At Lund Institute of Technology a programme has been developed, using the solver in ANSYS.

At Fraunhofer UMSICHT the software system BoFiT has been developed which is now distributed by the company ProCom. It was designed in co-operation between research institutes, engineering offices and energy supply companies to support the operation of DH-systems. BoFiT enables the optimisation of different operating fields and time horizons for all DH-supply systems no matter what size, production plant, organisation and product structure. One module of this software system is a platform which enables the simulation of the dynamic operation of DH-systems and the calculation of optimal control settings for the circulation pumps. Loops as well as DH-systems with more than one supply unit can be modelled and thermohydraulic calculation can be carried out in order to determine dynamic temperature and pressure states of the network. Beside plant and consumer models it is also possible to model the network's transport and heat storage characteristics. The objective of the "BoFiT" development was to establish a durable optimisation tool which gives the possibility to evaluate the applicability of direct heat storage processes and to consider also hydraulic transport boundaries in daily operational planning as well as the optimisation of the supply temperature to determinate the steady state operational optimum of the DH-system in a generally way.

MEK DTU and Risø have developed a programme called DH SIM, which was used in previous work, including the IEA Annex VI work. DH SIM has been developed to treat heat loads as time series – in contrast to most commercial programmes that treat the heat loads in the connected buildings in a simple way (annual values and a time factor to get instantaneous load, and often with the same cooling in all buildings).

DH SIM also has a facility to implement different models for the house stations, for example the equations for a plate heat exchanger is solved to give realistic return temperatures from the heat exchanger. A 2-string radiator system and a hot water system can also be modelled. In the optimisation of the DH system, the supply temperature is often changed from the actual value to

higher or lower values. In this respect it is important that the thermal response of the house station is modelled correctly.

At present DH SIM can only simulate DH networks without loops and can only handle one production unit. DH SIM uses the so-called "node model" for calculating temperature dynamics, Benonysson (1991), Pálsson (1997).

#### 2.2. Aggregation of District Heating Systems

Chapter 2.2.1 is a quotation from Larsen, Bøhm and Wigbels<sup>2</sup>.

#### 2.2.1. Aggregation Methods and Models

The Danish and German methods are rather similar, but with some important differences. Below these will shortly be discussed. Both methods are defined for a steady state situation, but nevertheless they are with good accuracy used for situations with time variations.

Both methods have the same building blocks:

- A model for changing a tree structure into a line structure.
- A model for removing short branches.

Moreover, the German method has a model for the simplification of loops.

To change a tree structure into a line structure the basic operation is illustrated in Figure 2-1.



Equivalent grid

Figure 2-1. Changing tree structure into line structure.

Table 2-1 shows which variables are conserved by the method of aggregation.

<sup>&</sup>lt;sup>2</sup> Larsen, H.V., Bøhm, B. and Wigbels, M. (2004): "A Comparison of Aggregated Models for Simulation and Operational Optimisation of District Heating Networks". Energy Conversion and Management (2004) 45/7-8, pp. 1119-1139.

|                            | German method<br>conserves | Danish method<br>conserves |
|----------------------------|----------------------------|----------------------------|
| Pipe length                | LA + LB = L2               | No                         |
| Pipe inner diameter        | No                         | DB = D2                    |
| Water volume               | Yes                        | Yes                        |
| Delay                      | Yes                        | Yes                        |
| Mass flow                  | Yes                        | Yes                        |
| Heat load                  | Yes                        | Yes                        |
| Heat loss from supply pipe | No <sup>3</sup>            | Yes                        |
| Heat loss from return pipe | No <sup>1</sup>            | Yes                        |
| Pressure drop              | Yes                        | Not considered             |

Table 2-1. Comparison of aggregation methods of tree structures.

To simplify nodes and consumer in branch situations the German and Danish methods differ with respect to what sub-system is regarded. The German method removes a node, replacing two branches by one, whereas the Danish method removes a (short) branch, replacing three branches by two. This is shown in Figure 2-2.

German method:



Figure 2-2. Removing a short branch.

Table 2-2 shows what variables are conserved by the method of aggregation.

|                            | German method<br>conserves | Danish method<br>conserves |
|----------------------------|----------------------------|----------------------------|
| Pipe length                | Yes                        | Yes                        |
| Pipe inner diameter        | No                         | No                         |
| Water volume               | Yes                        | Yes                        |
| Delay                      | Yes                        | Yes                        |
| Mass flow                  | Yes                        | Yes                        |
| Heat load                  | Yes                        | Yes                        |
| Heat loss from supply pipe | No <sup>1</sup>            | Yes                        |
| Heat loss from return pipe | No <sup>1</sup>            | Yes                        |
| Pressure drop              | Yes                        | Not considered             |

Table 2-2. Comparison of aggregation methods of removing short branches.

<sup>&</sup>lt;sup>3</sup> The total heat balance of supply pipe and return pipe together is kept

Both methods consider a steady state situation, i.e. a situation with no time variations. In the Danish method it is assumed that all (primary) return temperatures from the heat loads are equal. This leads to an aggregated grid with heat loss coefficients independent of temperatures. In contrast to this, in the German method it is assumed that the return temperatures are constant in time. The heat loss coefficients are adjusted so that the heat balance of the supply pipe together with the corresponding return pipe and the connected consumer is kept.

The two methods have different starting points in the development of aggregated grids. The German method conserves temperatures in all nodes (in the steady state situation). Since also volume and mass flow are conserved this implies that heat losses from the physical and the aggregated grids are not exactly the same. This holds even in a steady state situation with the same temperature in all pipes. Heat loss coefficients found by the German method can be negative in situations where loops or branches are aggregated. For compatibility to different simulation platforms it is possible to configure the algorithm so that the heat loss coefficients remain positive. In this case higher variations between aggregated and not aggregated networks have to be accepted.

The Danish method, however, focuses on heat loss, which is conserved (in the steady state situation). Consequently the node temperatures of the physical and aggregated grids are not exactly the same.

Pressure drop in the pipes is not considered by the present Danish method whereas the German method adjusts the surface roughness or the additional resistant caused by elbows etc. for each pipe in the aggregated grid in order to preserve pressure in each node. An additional resistant found by this method can be negative.

Assuming that the software program used to simulate the operation of the aggregated grid can handle negative heat loss coefficients and additional resistances, such values will not bring about any problems.

During the aggregation the Danish method keeps track of all physical loads and supplies information on how each physical load is divided between the aggregated loads. At the moment such information is not supplied by the German method that only gives data on the size of each aggregated load, but not on the origin of this load.

Currently, loops can only be simplified by the German method. This strategy handles loops in two ways:

- Transformation of a loop into serial pipes.
- Splitting of a loop into two serial pipes and one branch.

For steady state simulations in the latter case the heat balances of the loops can be kept. For the simplification of loops into serial pipes low errors have to be accepted. It is up to the user which method he prefers. The former case leads to a faster simplification. To remove a loop one has to identify a specific node where the mass flows (divided at the input into the loop) flow together again. Therefore, loops, where the flows meet at another node (as can occur if the consumers' load varies in time) can only be simplified by accepting some errors. Usually, these loops are only simplified if absolutely necessary.

#### 2.2.2. Model of Consumers' Heating Installation

The German method uses a prescribed return temperature, which is a function of heat load (outdoor temperature) and supply temperature.

The Danish method has a specific model for the heating installation, which calculates the return temperature as a function of heat load, primary supply temperature, secondary temperatures and the heat transfer area (kA) of the heat exchanger (or radiator). Different types of heating installation models have been developed, but in this paper it is assumed that all consumers are connected through plate heat exchangers.

In the aggregation process the Danish method traces the heat load and temperature time series from the real consumers to the aggregated consumers and then a new kA-value is calculated for the aggregated consumer.

#### 2.2.3. Structure of Aggregated Networks

The Danish method will, if applied straightforward, result in a line network. However, as previously documented in Pálsson et al. (1999), DH networks could be aggregated in ways that preserve parts of the original tree structure.

The German method can be applied in a similar way. Depending on the parameters controlling the aggregation process, the aggregated system could be a line network or a network with some parts of the tree and/or loop structure preserved.

#### 2.3. Optimisation of DH-Systems

#### 2.3.1. The Danish Optimisation Approach

The work carried out so far has primarily addressed DH systems with one production plant. The goal is to found an optimum supply temperature for the coming period, for instance 48 hours.

The object function typically includes the following:

- either production cost or heat loss cost,
- pumping cost, incl. variable efficiency of the pump,
- tariff costs (penalties for bad cooling or for large load variations),

The constraint function typically includes:

- capacity of the circulation pump (pumping curve)
- maximum permissible change in supply temperature from one time step to the next
- start and stop conditions (same supply temperature in the beginning and in the end).

First the optimisations were made with (aggregated) pipe models based on the "element method" and programmed in Matlab 4.2 and utilising the Matlab function "*constr*". In Matlab 6.5, the function "*constr*" does not work properly, and instead the function "*finincon*" had to be used.

In the EFP project an interface between Matlab 6.5 and DH SIM has been built enabling DHSIM simulations to be called from Matlab.

It was found that the newest results differ slightly from the old ones, bearing in mind that two different pipe models and two different optimisation routines are being used. We have noticed that the *fmincon* function results in a more oscillatory behaviour of the optimum supply temperature than the *constr* function.

#### 2.3.2. The German Optimisation Approach

At the Fraunhofer Institute UMSICHT a nonlinear model has been developed facilitating the dynamic optimisation<sup>4</sup> of combined heat and power production systems. This strategy is called "dynamic supply temperature optimisation" and enables the use of the DH-network itself as a large heat storage causing no additional investment cost.

The supply temperature optimisation aims at finding the operating point at which the power requirements (heat and electricity) of the consumers can be covered with minimum operating cost. In order to determine the optimal values of the variables, the system performance as well as the technical and contractual restrictions have been considered in the mathematical optimisation model. These are e.g. the energy purchase contracts, the characteristics of the energy conversion plants, the power requirement of the consumers and the dynamic behaviour of the DH network. These connections have been described by equations and inequations, in which optimisation

<sup>&</sup>lt;sup>4</sup> In this context not the dynamic programming but the optimisation over a certain time period is meant

variables and model coefficients are linked together. On the basis of configuration and calculation data an optimisation model has been formulated under application of modern optimisation procedures. As results of these optimisation model the optimal courses of the supply temperatures of the individual suppliers, the electrical and thermal input powers as well as the storage powers etc. can be received.

#### Scientific and Technical Objectives

In order to determine the optimisation potential of heat storage processes in the DH-network of a DH or CHP system, an algorithm has been developed taking into account the dynamic character of a DH-network. As input data, the technical and economic structure of the energy production facilities, the energy purchase as well as the DH-network including heat accumulators and the prognoses of the thermal and electrical power requirements of the consumers is needed (see ). This prognoses data must be provided for the time period considered for the optimisation.

Based on this data an optimisation model will be generated which enables the consideration of the dynamic thermo-hydraulic behaviour of DH and CHP systems due to dynamic energy production, distribution and demand. The dynamic pumping power requirement along with the heat loss has to be modelled. Special consideration must be taken towards a suitable mathematical formulation for the complex dynamic processes in the transport system since this is essential when modelling the heat storage processes in the DH-system. The unit commitment, the load dispatch as well as the operation of the bypasses and especially the supply temperatures in all heat production plants must be considered to facilitate the full potential of the energy supply system due to its optimisation by the heat storage processes.

#### Mathematical model

In the mathematical it is distinguished between energy supply and DH network. The energy supply consists of systems for the energy conversion, the contracts for the external supply of heat and electrical power as well as the electricity network. They have to be set up in such a way that the supply temperature is declared as optimisation variable. The DH-network is the most important part of the mathematical model. In this model the thermo-hydraulically dynamic behaviour of the DH network has to be modelled. This submodel is based on methods of the thermo-hydraulic network simulation.



Figure 2-3. Heat storage optimisation model

The mathematical model is based on the separation of the optimisation period into equidistant time steps with the time increment  $\Delta t$ . The time steps are chronologically numbered. Due to the assumption of a quasi steady state hydraulic behaviour of the system the steady state hydraulic model has to be set up for each time step.

Due to the convective heat transport and the large delay times in some pipes a dynamic thermal model has been developed, which describes the delay time characteristic of the network. For the other components of the DH network the delay time behaviour can be neglected.

For each element of the DH-network a adequate nonlinear model has been developed. All separate elements are set up to an overall system of linear and nonlinear restrictions. It can be distinguished between:

| • | • Power plants (Heating unit, CHP Unit of different types) |               | linear    |
|---|--|---------------|-----------|
| • | Heat exchanger   | $\Rightarrow$ | nonlinear |
| • | Valves   | $\Rightarrow$ | nonlinear |
| • | Pumps  | $\Rightarrow$ | nonlinear |
| • | Pipes  | $\Rightarrow$ | nonlinear |
| • | Consumer   | $\Rightarrow$ | linear    |
| • | Purchase contracts   | $\Rightarrow$ | linear    |
|   |  |               |           |

#### **Objective Function**

Solving economic questions the attainable profit often represents the quality of a decision. However, the incomes of the energy supply company cannot be influenced by the operation mode and therefore they represent a constant in the context of operational planning. That is why instead of the profit the operating costs are used for the evaluation of the quality of an operation mode.

The costs of the energy purchase as well as of the fuel supply for the production systems are the only costs influenced by the operation mode of the power supply system. Therefore, the total costs K for the energy purchase and the fuel supply are formulated as objective function of the optimisation problem.

$$\sum_{e \in GHWK} K_e + \sum_{e \in GTHWK} K_e + \sum_{e \in SB} K_e + \sum_{e \in HW} K_e + \sum_{e \in WB} K_e = 0$$
(1)

| With   |  |
|--------|--|
| GHWK:  | Set of production units with backpressure turbines   |
| GTHWK: | Set of production units with gasturbines             |
| HW:    | Set of production units with heat only boilers (HOB) |
| SB:    | Set of electricity purchase contracts                |
| WB∙    | Set of heat purchase contracts                       |

Target of the operational planning is the determination of the operation mode with the minimum operating costs. All the other equations represent constraints of the optimisation problem, which have to be kept.

#### 2.4. Demand Side Management in DH-Systems

Demand side management (DSM) in the connection of district heating systems is here mainly focused on energy suppliers. In addition to consumer's own control system also the heat delivery and heat storing system make load control possible. Then we can talk about DSM of heat load in general. Load management is defined as direct or indirect control of consumers' load.

The economic benefits of DSM are best achieved in combined heat and power production plants (CHP). More electric generation is possible when electric demand is high and the market price is high enough. CHP production is becoming more utilised when district heat market is wider used in Europe. DH penetration is almost 100 % in Nordic countries (especially in Finland and Denmark), but there is potential to double the DH market in Europe. Lower environmental impacts of CHP are concrete advantages in addition to economic benefits.

Basic energy supplies with low-cost fuels can be increased in the time of varying loads, low consumption and in the case of disturbances in energy production by using load and demand side management. Thus boiler start up or stand by can be avoided.

Heat load in buildings could be increased or decreased in some hour period by temperature control. Thermal capacity of the building compensates small temperature variation so the consumer does not feel the management. Tap water load is not limited in DSM.

District heating network as heat storage is operated by disturbed outgoing temperature compared to the set point. In that way the network is charged or discharged by temperature. Time delays of

the control depend on extent of the network. Delays are longer during small load period than high load period. Charging time of the network storage is typically 2 to 3 hours and after that the storage is discharged by itself because of the consumers' control equipment. Separated heat storage, e.g. large steel tanks, can be operated independent of the DH consumer's system. The storage tank is used for optimisation of the heat supplies especially in CHP plants. When charged the tank is like a consumer and when discharged it is like a heat supply.

Same types of demand and supply side management methods are suitable to DH-systems in Northern countries and also in Europe. There are some differences for design values of district heating systems in Europe, but still the operation principles are same. The most remarkable difference is the direct or indirect connection of consumers. Differences between electrical systems are remarkable in Europe and therefore it has also impacts to economy of DSM in DH side. Design of DSM methods is strong depended on local circumstances. Generally district cooling has important role in warm climate countries and the control of heat loads depending on electricity demand is becoming more important in cold climate countries.

### 3. Fundamentals

#### 3.1. Comparison of the Danish and German Aggregation Approach

In the IEA work aggregated models developed by the Danish and German methods were further tested and compared. Chapter 3.1 is a quotation from Larsen, Bøhm and Wigbels<sup>5</sup>. Here the results for the DH system of Ishoej, Copenhagen, are presented as test case. This system has rather few connected loads (23) and a very high line heat demand. The special feature of the Ishoej system is that the data collection system enables information on instantaneous heat loads and return temperatures from the heat exchanger stations.

#### 3.1.1. The Ishoej District Heating System

Ishoej is a suburb of Copenhagen, located 17 km south-west of the city centre. The built-up area consists mainly of blocks of flats, semidetached houses, institutions and shopping centres. Many of the buildings were erected in the 1970s.

The DH system was built in 1982. Today, some 8000 dwellings, five schools and the city centre with many shops and institutions are supplied from the DH system. All consumer installations are indirectly connected through 23 substations (each substation consists of one or two plate heat exchangers).

The distribution network is shown in Figure 3-1. It is made of preinsulated pipes, mostly with standard insulation thickness, and in pipe dimensions from 48 to 356 mm. The total length of the network is approximately 8.3 km. As all connected buildings are situated within a small area, the line heat demand is high, approximately 42 GJ/m, and the annual heat loss (from the primary network) is only approximately 3%.



Figure 3-1. The distribution network in Ishoej with 23 substations.

<sup>&</sup>lt;sup>5</sup> Larsen, H.V., Bøhm, B. and Wigbels, M. (2004): "A Comparison of Aggregated Models for Simulation and Operational Optimisation of District Heating Networks". Energy Conversion and Management (2004) 45/7-8, pp. 1119-1139.

The Ishoej DH company has installed an advanced control and supervision system, which, among other tasks, stores data from the substations and the plant at a five-minute interval.

At a typical substation the following data is available:

- primary and secondary supply temperature
- primary and secondary return temperature
- pressures in the supply and return line
- accumulated heat meter readings (energy and volume).

At the Ishoej plant the production by the boilers and the amount of heat delivered from the VEKS system are available, as well as flow, temperature and pressure measurements.

5 minutes-data from December 19-24, 2000, is used. The heat loads at the substations were obtained by filtering the heat meter data. Heat production data at the Ishoej plant was obtained from VEKS. In this period the boilers were used only a couple of hours.

Manual reading of the heat meters had taken place on December 11 and 18/2002 For those substations where no data was available, a heat load series was constructed from other substations with data, taking into account the type of building (block of flats, school, etc.) and the heat consumption. Despite the uncertainty associated with this way of generating the missing data, the result is quite good as is shown in Figure 3-2. Here the measured heat production at the Ishoej plant is compared with the sum of the heat loads in the substations.



HEAT LOAD ISHOEJ Dec. 19-24, 2000

Figure 3-2. Measured heat production at the plant and the sum of the (filtered) heat loads in the substations.

#### 3.1.2. Modelling the Ishoej DH system

In the modelling of the Ishoej system the generated data set has been used as input files to a general simulation program. Time series for heat load as well as for secondary forward and return temperatures have been used for each substation. All substations were modelled as one plate heat exchanger, and the kA values were estimated from the measured heat load and from the measured primary and secondary supply and return temperatures.

#### 3.1.3. Aggregation the Ishoej DH system

The detailed model of the Ishoej network consists of 44 branches and 23 loads. Two methods, i.e. the Danish and the German methods, have been used to aggregate the physical grid. The Danish aggregation method is described in details in Pálsson et al. (1999) and Larsen et al. (2002).



Figure 3-3. Aggregated networks in Ishoej. Danish models D\_23, D\_5 and D\_2.

Likewise, Loewen (2001) gives a description of the German method. The aggregated systems are shown in Figure 3-4. These aggregated systems all represent the physical system shown in Figure 3-1.

#### 3.1.4. Simulation the Ishoej DH system

Time series covering the period from December 19, 2000 12:00 until December 24, 2000 24:00 with time steps of 5 minutes are used in the simulations of the physical system.

For the aggregated systems, where substations have been combined, heat loads are not modelled in the same way for the Danish and for the German models. Weighted sums of measured time series (heat load and secondary forward and return temperatures) are used for the Danish aggregated substations.



Figure 3-4. Aggregated networks in Ishoej. German models G\_20, G\_10, G\_6 and G\_2.

The German method of aggregation does not supply information on how to calculate time series for the aggregated loads using information on the individual physical loads. Instead the sum of all time series for physical heat loads is distributed between the aggregated loads, i.e. all aggregated loads are varying proportionally. For secondary forward and return temperatures the same constant values are used for all aggregated loads. These constant values are calculated as weighted averages of the measured time series.

Regarding the supply temperature from the plant two situations are considered:

- The supply temperature is as measured (i.e. varying around 105 °C). See Figure 3-5.
- The supply temperature is 100 °C for a period and then it is suddenly increased to 110 °C.



Figure 3-5. Measured supply temperature from the plant.

#### 3.1.5. Results for the Danish Method of Aggregation

Figure 3-6 shows the amount of heat supplied by the DH plant for the physical system and for an aggregated system with 5 branches found by the Danish method (system  $D_5$ , Figure 3-3). The supply temperature is as measured. In Figure 3-7 the difference between the two time series in Figure 3-6 is shown.



Figure 3-6. Heat production supplied by the plant for the physical system and for aggregated system D\_5.



Figure 3-7. Error in heat production for aggregated system D\_5 as compared to the physical system.

In Fig. 23 an aggregated system with 6 branches found by the German method (system G\_6, see Figure 3-4) is compared with the physical system. The supply temperature from the plant is 100  $^{\circ}$ C and then suddenly increases to 110  $^{\circ}$ C. In Figure 3-9 the difference between the two time series in Figure 3-8 is shown.



Figure 3-8. Heat production supplied by the plant for the physical system and for aggregated system G\_6. A step function is used as supply temperature from the plant.



Figure 3-9. Error in heat production for aggregated system  $G_6$  as compared to the physical system. A step function is used as supply temperature from the plant.

The curve in Figure 3-9 is much smoother than the curve in Figure 3-7. The reason for this is that the supply temperature from the plant in Figure 3-9 is constant (except for the step) whereas the supply temperature in Figure 3-7 is a measured time series with variations.

#### 3.1.7. Evaluation of Aggregated Models

To assess the quality of a specific aggregated model, time series for the amount of heat supplied by the plant are found by simulating the aggregated system as well as the physical system. The standard deviation of the error between these two time series is then used as a criterion for the quality of the aggregation.

Another criterion is also introduced. It is based on the standard deviation of the error between the return temperature to the plant calculated for the physical system and for the aggregated system.

The following figures show how the standard deviation of error increases as the number of branches is reduced. The heat production at the plant is considered in the figures to the left whereas the return temperature at the plant is focused on in the figures to the right.

Only models made by the Danish method of aggregation are considered here. German models will be dealt with below.

For the physical system all loads and secondary forward and return temperatures are represented by measured time series. For aggregated systems, however, time series for loads and secondary temperatures are calculated as weighted averages of measured series.

Regarding supply temperature from the plant two different situations are shown:

- A measured time series is used as supply temperature from the plant (approximately 105 °C).
- A step function is used as supply temperature from the plant (step from 100 to 110 °C).



Figure 3-10. Standard deviation of error. The measured time series is used as supply temperature from the plant.



Figure 3-11. Standard deviation of error. A step function is used as supply temperature from the plant.

It is seen that the number of branches can be reduced to 3 without increasing the error very much. Model  $D_1$  with only one branch and two loads has a standard deviation of the error (defined on basis of heat production at the plant) of approximately 2 %, but the average error over the simulated time period is as small as 0.01 %.

For dynamic information the German method of aggregation does not supply information on how the physical loads are divided among the aggregated loads. Therefore the capability of such aggregated grids has to be tested with the following load model: For the physical system as well as for all aggregated systems, all load time series are modelled as fixed percentages of the time series for the total load. That is, all loads are varying proportionally and adding up to the correct total load series. Secondary forward and return temperatures are constant and have the same values for all loads. These values are calculated as weighted averages of the measured temperature time series. Also the Danish grids are tested with this load model.

Regarding supply temperature from the plant the same two situations as above are shown:

- A measured time series is used as supply temperature from the plant (approximately 105 °C).
- A step function is used as supply temperature from the plant (step from 100 to 110 °C).

From the figures below it is seen that the number of branches can be reduced from 44 to three when using the Danish method of aggregation without significantly increasing the error in heat production or return temperature at the plant. In case of the German method, the number of branches should not be reduced much below ten to guarantee a standard deviation below 0.3 % for the error of heat production and 0.05 °C for the error of the return temperature.



Figure 3-12. Standard deviation of error. The measured time series is used as supply temperature from the plant. A simple load model is used.



Figure 3-13. Standard deviation of error. A simple load model is used.

#### 3.1.8. Conclusions

It can be concluded that the number of pipes can be reduced from 44 to three when using the Danish method of aggregation without significantly increasing the error in heat production or return temperature at the plant. In case of the German method, the number of pipes should not be reduced much below ten to guarantee the same errors in case of the Ishoej DH system.

The work on aggregated network models will hopefully be continued in future research projects. Some items that could be improved in the Danish and German methods are clear from Table 2-1 and Table 2-2 above. The Danish method, for instance, could be improved by the possibility to simplify loops and to conserve the pressure in the DH networks. Likewise, it would be an improvement to the German method if could supply information on how each physical load is divided in dynamic simulations between the aggregated loads.

#### 3.2. Demand Side Management

#### 3.2.1. Modelling of the Buildings

The heat consumption peaks in buildings usually occur in the morning and/or in the evening due to simultaneous starting and shut-down of building heating systems, especially in commercial buildings (offices, schools, etc.). These time bounded peaks in typical buildings can be easily shifted by timer controlled DSM measures. A more sophisticated DSM can also include active reducing of certain key customers' load so that their load would be high when the other's is low and vice versa.

A calculation tool for buildings has been developed for quick evaluation of proper DSM possibilities. The characteristic model of buildings is described using the thermal capacity-resistance description.

The characteristic model of buildings is described using thermal capacity-resistance model as shown in Figure 3-14. The model calculates also mass of the buildings divided into external walls, roof, bottom, internal walls, and internal ceilings

Convection heat cells include heat power from heating or cooling, electrical equipment, lighting, people, solar, etc. and radiation heat cells include radiation power from the same cells.



Figure 3-14. Capacity-resistance model for adjacent rooms of the building, Temperatures: T0 = outdoor, Ti = internal, Tw = coat wall, Tiw = internal wall or ceiling, Twi = medium temperature of internal surfaces, Tf = floor, Tg = ground.

Heat balance of the nodes can be described.

Convection

$$C_{i} \cdot \frac{dT_{i}}{dt} = P_{c} + P_{vent} - G_{w} \cdot (T_{i} - T_{0}) - G_{win} \cdot (T_{i} - T_{0}) - G_{s} \cdot (T_{i} - T_{s}), \qquad (2)$$

where  $C_x = hA\rho c_p$  is thermal capacity of X; h is height or thickness, A is area,  $\rho$  is density of material and  $c_p$  is specific heat capacity of the material. The thermal conductance is G = UA; U is thermal transmission factor.

Radiation

$$C_{s} \cdot \frac{dT_{s}}{dt} = P_{r} + P_{sol} + G_{w} \cdot (T_{s} - T_{i}) - G_{w1} \cdot (T_{s} - T_{iw})$$
(3)

$$C_{iw} \cdot \frac{dT_{iw}}{dt} = G_{iw2} \cdot (T_i - T_{iw}) + G_{iw1} \cdot (T_{i2} - T_{iw}), \qquad (4)$$

If  $T_i$  is equal to  $T_{i2}$  and  $G_{iw2}$  equal to  $G_{iw1}$ , the equation (4) can be written

$$C_{iw} \cdot \frac{dT_{iw}}{dt} = 2 \cdot G_{iw} \cdot (T_i - T_{iw})$$
<sup>(5)</sup>

$$C_{w} \cdot \frac{dT_{w}}{dt} = G_{w2} \cdot (T_{wi} - T_{w}) - G_{w1} \cdot (T_{w} - T_{0})$$
(6)

Thermal power of solar radiation is

$$P_{sol} = \Psi_{sc} \cdot \alpha_{w} \cdot q_{sol} \cdot A_{w}, \qquad (7)$$

where  $\psi_{sc}$  is a shadow factor for the building and  $\alpha$  is a factor for technical properties of the window.  $q_{sol}$  is solar radiation to the surface.

 $P_r$  is radiation power of occupation (lighting, electrical machines, etc.) and  $P_c$  is convection power of occupation (lighting, electrical machines, warm tap water, etc.).

Heating capacity for ventilation i

$$P_{vent} = q_a \cdot c_{pa} \cdot \rho_a \cdot (T_0 - T_i) \cdot (1 - \eta_{hrs}), \qquad (8)$$

where index a is a property of the air, q is air flow,  $c_p$  thermal capacity,  $\rho$  density and  $\eta$  is the efficiency of the heat recovery system.

When we operate with temperature control in buildings for DSM operation, the thermal response of the building must be known. When we know the material, which the building is made of, we can evaluate the thermal response of the building.

$$\rho \cdot V \cdot c \cdot \frac{d\theta}{dt} = G \cdot \theta, \tag{9}$$

where  $\rho$  is material density, V is material volume, c is specific thermal capacity of materials, G is conductance of the building and  $\theta$  (=T-T<sub>out</sub>) is temperature compared to reference temperature. G is also  $\phi/\theta$ , where  $\phi$  is thermal loss through conductance of the building. Then we have

$$\boldsymbol{\theta} = \boldsymbol{\theta}_0 \cdot e^{-\frac{G}{\rho \cdot V \cdot c} \cdot t}, \qquad (10)$$

where  $1/\tau = G/\rho Vc \implies$  is the time constant of the building. The active part of the building capacity consists of 10 % of the materials inside the building and takes part of the inside temperature control. When the heating is cut off, the building starts cooling (cut period) and when the heating is turned on, the building starts warming (lift period).

#### 3.2.2. Optimisation of the used Production Capacity of DSM

The problem of determining an optimal operation schedule for a heat and power production system having a heat storage is encountered both at the short term control and at the investment planning phase of the combined energy system. At the short term control the operation schedule is to be determined for the next week e.g. At investment planning we simulate the operation of the system over a year, and calculate the production costs for different configurations. For every configuration, the production costs are computed on the basis of optimal use of the resources, and these optimal costs form the basis of the economic evaluation of the heat storage investment.

The optimisation problem becomes extensive and complicated, especially for systems having some or several of the following features:

- several types of plants producing heat, power, or both, with different production characteristics,
- heat storages, hydropower production, water reservoirs, constraints on the flows and storage levels,
- emissions constraints,
- time or temperature dependent production, time dependent tariffs,
- uncertainties concerning the demand, production, prices etc., and
- costs associated with start-ups of the plants.

Even with the present computational capacities it is impossible to include all these features in an integrated mathematical planning and optimisation model of the energy production system. We discard the stochastic features (uncertainty of demand e.g.), and the non-convex features (start-up costs, non-convex production characteristics) of the optimisation problem for the production. This leads to the following formulation.

#### 3.2.3. Description of the Optimisation Problem

The linearised optimisation problem for the energy production system can be written as follows:

min C = 
$$\sum_{t=0}^{T-1} [a(t) \cdot x(t) + b(t) \cdot u(t)] - a(T) \cdot x(T),$$
 (11)

$$x(t+1) = x(t) + A(t) \cdot x(t) + B(t) \cdot u(t) + s(t),$$
(12)

$$x(0) = q,$$
 (13)  
 $G(t) \cdot x(t) + D(t) \cdot u(t) \le f(t),$  (14)

$$u(t) \ge 0, \tag{15}$$

where the time is discrete: t = 0, 1, ..., T-1.

The unknown variables of the model include the states (levels) of the storages, and these form the state vector x(t). The unknown production variables form the control (production) vector u(t). Typically the state vector has only a few components, but the number of control components may be some dozens or some hundreds.

The function C in equation (11) is the objective function, total operational costs for production and purchases of energy over the time period T. The last term is the value of the remaining storages at the end of the period. The given vectors a(t) define costs associated with storage of energy. The cost vectors b(t) define the operational production costs.

The dynamic vector in equation (12) states energy balances for each energy storage: the contents of the storage at time t+l, x(t+l), equal the contents x(t). plus losses A(t)x(t) (proportional to the energy contents), plus charges and discharges B(t)u(t), plus the given inflow of energy s(t). The inflow term is characteristic for water reservoirs, e.g. The initial contents of the storages form the constant vector q. see eq. (11).

The vector inequality (14) contains all the constraints on the state x(t), and all the combined statecontrol constraints binding the state and the control u(t). The matrices G(t) and D(t) constitute a linear and stationary production model of the energy system at time point t. Owing to time- or temperature-dependent characteristics of production units, maintenance outages of plants, and similar reasons, the production model is dependent of time. The given vectors f(t) contain the capacities of the plants, and the demands for heat and power.

#### 3.2.4. Solution of the Problem through the Maximum Principle

The problem (9) - (13) is a dynamic linear programming (DLP) problem. In principle, it can be solved as a single LP problem, and also in practice this is feasible for small and for medium-sized problems. However, for large systems, and for long time-periods, the number of unknowns grows so large, that solving (9) - (13) as a single problem is no longer possible, and some kind of decomposition is required.

The discrete maximum principle of Pontryagin leads to an especially attractive decomposition of the problem. The principle gives necessary conditions of optimality for convex and discrete optimal control problems, and for DLP problems these conditions are known as duality relations for DLP problems. Alternatively, for DLP problems, the conditions can be derived directly by applying the duality theory of linear programming.

The essential result of the maximum principle is, that there exists a time-dependent vector p(t) of storage values (prices, one component of p(t) for each component of the state x(t)), such that for each time point t the optimal production u(t) is an optimal solution for the sub-problem at time t, (16) - (19).

| min | $b'(t) \cdot u(t)$ | , (16) |
|-----|--------------------|--------|
|-----|--------------------|--------|

$$D(t) \cdot u(t) \le f'(t) = f(t) - G(t) \cdot x(t),$$
(17)

$$\mathbf{u}(\mathbf{t}) \ge \mathbf{0} \,, \tag{18}$$

where

$$b'(t) = b(t) - B^{T}(t) \cdot p(t+1),$$
 (19)

The optimal price vector i.e. the price vector giving the optimal solution u(t), t = 0, 1, ..., T satisfies the vector difference equation (20) with the final condition (21). The dual control A(t) in (20) is an optimal solution for the (LP) dual of the problem (16)-(19), and the difference equation is called the dual equation.

$$p(t) = p(t+1) + A^{T}(t) \cdot p(t+1) - G^{T}(t) \cdot \lambda(t) - a(t), \qquad (20)$$

and

$$p(T) = a(T)$$
. (21)

The maximum principle conditions for the determination of an optimal solution to the problem (11) - (15) are the following:

(i) the primal and the dual difference equations (12) and (20) together with the boundary conditions (13) and (21),

(ii) for each t = 0, 1, ..., T-1, the minimum conditions (16) - (19) determining the optimal control u(t),

and

(iii), for each t, the LP dual of (16) - (19), giving the optimal dual control.

#### 3.2.5. The primal-dual Iteration

The structure of the maximum principle conditions precludes a direct solution of the optimal operation of the system, and suggests the following primal-dual iteration method:

- a suitable dual trajectory p(t), t = T, T-l, ..., 1 is chosen as the starting point for the iteration.
- the state equation (12) is integrated step by step forward in time starting from the given initial condition (13).
- for each t the control u(t) is solved from (16) (19), applying the chosen price vectors p(t+1), and the state vectors x(t) generated in the course of the present iteration. After the whole state trajectory has been computed, we turn to the dual side of the conditions.
- the dual state equation (20) is integrated backward in time starting from the final condition (21).
- The dual control  $\lambda(t)$  is solved from the LP dual problem of (16) (19), using the newly solved state trajectory x(t), and the dual state p(t+1) generated during the current iteration.

This new price system is used in the next iteration forward in time for the determination of a new primal solution. An optimality criterion based on the duality theory gives an upper bound to the distance from the true optimum.

It can be proven, that for problems satisfying certain assumptions, the simple primal-dual iteration converges (the iteration has a stable fixed point), see Tamminen (1979). However, in the majority of interesting cases these conditions are not satisfied, and the iteration process does not converge, but oscillates in the set of solutions. In fact, in these cases, the absence of convergence is a direct consequence of the structure of the problem.

On the other hand, the efficiency of the decomposition trough the maximum principle makes the approach very attractive, and it has led us to seek for heuristic means to stabilise the behaviour of the algorithm. In principle, there are two possibilities: we can add to the problem either auxiliary constraints or modifying cost terms in such a way that the algorithm is stabilised, and it generates a solution near the optimum. We have experimented with both methods, and experience shows that a suitable method for the stabilisation can usually be found. However, stabilisation often requires trimming of the algorithm according the problem.

#### 3.2.6. Computational Experiences

At VTT Processes we have developed a computer system for the optimisation of energy production (including storages) applying the approach based on the discrete maximum principle. Heuristic methods are used for the stabilisation of the algorithm. The system consists of a library of production models, and of programs for setting up and solving the production optimisation problems. The system has been installed at several large utilities in Finland, and it has also been used by VTT Processes on the economic assessment of heat storage investments.

### 4. Data Collection

#### 4.1. The Oberhausen District Heating System

The district heating system of the city of Oberhausen which is owned by the energy supply company of Oberhausen (EVO) consists of three subsystems; a northern part in the district "Sterkrade", and a southern district in main "Oberhausen". These subsystems are connected via a hydraulically separated heat transport line where also one big consumer and a waste incineration plant with 35 MW heat and 25 MW power production are connected. Within the EVO district heating system three CHP plants are operated with a total heat and power production of 160 MW and 60 MW respectively. In the southern part a backpressure turbine is operated. Beside the heat input of the 60 MW gas turbine and plant 30 MW waste heat of a chemical production facility is coupled to the northern system.



Figure 4-1 The district heating system of the energy supply company of "Oberhausen" (EVO)

The figure above represents the structure of the EVO DH-network. In the year 2003 a number of 5912 substations were connected to the pipeline system. The length of the DH-network is currently 181.3 km. The nominal heat load of the system is 555 MW. 2003 the company EVO produced 534 GWh heat and 160 GWh electricity in own production units.

#### 4.2. Næstved District Heating System

Næstved is a town of 47500 inhabitants, located in the southern part of Zealand, Denmark. The District Heating company is consumer-owned (A.m.b.a) and it has 3460 consumers. It was established in 1965. Today, 90% of the heat production comes from the combined incineration and CHP plant FASAN, while the rest of the heat is produced on natural gas. However, two of the five production plants can also use gas oil.
In the financial year 2003/2004 the maximum production was 66 MW, and the annual heat production was 743 TJ, of which 76 TJ was based on natural gas. 601 TJ was sold to the consumers, resulting in a heat loss of 19 % and a line heat demand of 4.1 GJ/m.

#### 4.2.1. The Distribution System

A sketch of the system is shown in Figure 4-2. The network consists of 78 km distribution pipes and 69 km of service pipes. There are only a few concrete ducts left from the start of the system. The supply and return temperatures are 85 / 47  $^{\circ}$ C in the winter period and 80 / 50  $^{\circ}$ C in the summer. There are a few thermostatic bypasses in the streets and at some consumers.

Næstved is separated in four zones that are hydraulically connected: Downtown area with the main stations Aaderupvej and Central Kanalvej, producing on gas and oil. The incineration plant FASAN supplies heat to Central Aaderupvej and Sank Joergen Park heat exchanger stations. There is a special single supply line from Aaderupvej to Sankt Joergen Park to increase the heat supply (without a return line).



Figure 4-2 Sketch of the Nastved district heating system

Parkvej is part of the downtown area but a shunt valve can lower the supply temperature to this area. The remote data acquisition system collects data from all 41 consumers in the Parkvej area. Little Næstved is the western part of the system supplied through a single pipe under the canal. Central H.C. Andersen is located in this area, utilising natural gas. Ejlersvej is the north-eastern part of the system with Central Ejlersvej and Central New Holsted, both using natural gas. A booster pump can be used to increase the supply to this area from the Downtown area.

There are circulations pumps at all production plants and at Sankt Joergen Park heat exchanger station. There are three booster pumps. Maximum capacity in the Downtown area is approximately  $1100 \text{ m}^3/\text{h}$ , and  $1500 \text{ m}^3/\text{h}$  for all circulation pumps in the system.

The differential pressure is approximately 2.8 bar.

# 4.2.2. Consumer Database

Of the 3460 buildings (consumers), 2640 are single family and semi-detached houses, 446 are blocks of flats and the rest offices and institutions. There is a remote reading system connected to approximately 560 consumers. Hourly values are collected weekly from the 260 largest consumers, and monthly values are collected from 300 consumers. Approximately 65% of the consumption is connected to the remote reading system.

In connection with the IEA project a special data collection was set up so that 5-minutes values were collected from 17 large consumers. These consumers are shown in Table 4-1.

# 4.2.3. House Stations

As the consumers are a mix of small and large consumers, the house stations vary from small direct connections to large indirect connections. Even among the large consumers are seven direct connected installations, cf. Table 4-1. Most consumers have a hot water tank for production of domestic hot water, connected in parallel with the heating system.

The design heat load shown in Table 4-1 is based on the radiator output at  $\Delta T = 55$  K. On the average the radiator factor (over-sizing) is 1.8. The design heat load does not include the domestic hot water systems.

| #        | Design | n heat load | Building ca     | tegory              | Heat met | ers 2004 |
|----------|--------|-------------|-----------------|---------------------|----------|----------|
|          | kW     | Direct      | Туре            | Floor               | Consump- | Cooling  |
|          |        | connection  |                 | Area m <sup>2</sup> | tion MWh | °C       |
| 20010003 | 846    | Yes         | Flats           | 8200                | 1016     | 37       |
| 20010006 | 880    | Yes         | Flats           | 9600                | 1318     | 30       |
| 20010009 | 2998   | No          | Institutions,   | 32000               | 6086     | 31       |
|          |        |             | offices, school |                     |          |          |
| 20010015 | 918    | Yes         | Semi-detached   | 15800               | 1638     | 29       |
| 20010017 | 1046   | No          | Flats           | 9000                | 903      | 25       |
| 20010047 | 1156   | No          | Public school   | 12800               | 1205     | 32       |
| 20010105 | 757    | Yes         | Nursing home    | 7000                | 1070     | 26       |
| 20010119 | 601    | No          | Offices         | 8700                | 1312     | 27       |
| 20010132 | 854    | Yes         | Flats           | 10500               | 1372     | 28       |
| 20010418 | 907    | Yes         | Semi-detached   | 15600               | 1690     | 27       |
| 26003114 | 801    | No          | Flats           | 9900                | 1489     | 28       |
| 26003116 | 409    | No          | Flats, offices, | 6800                | 1011     | 38       |
|          |        |             | shops           |                     |          |          |
| 26003117 | 1072   | No          | Public school   | 11000               | 1536     | 33       |
| 26003118 | 1336   | Yes         | Public school   | 11500               | 1712     | 38       |
| 26003702 | 1170   | No          | Flats           | 18000               | 1943     | 38       |
| 26004654 | 906    | No          | Old people's    | 5000                | 1104     | 23       |
|          |        |             | home            |                     |          |          |
| 26005102 | 831    | No          | Semi-detached   | 13800               | 2071     | 16       |
| Total    | 17488  |             |                 | 205200              | 28476    |          |

Table 4-1. Næstved. Design heat loads, building categories and measurements 2004.

## 4.2.4. Heat Accounting

The consumers pay for the energy consumption and for a fixed charge according to the radiator size (nominal design load).

## 4.2.5. Production Costs

For the simulation and optimisation work in this study we will apply a simple cost model.

Prices excl. of VAT:

Electricity for pumps: 196.45 USD/MWh

Heat from FASAN incineration plant: 50.10 USD/MWh, Maximum capacity 50 MW.

Production on natural gas: 80.04 USD/MWh (including efficiency of the boiler). This price is valid for production up to 30 MW. If the production on natural gas exceeds 30 MW, the extra gas consumption costs 263.10 USD/MWh.

Production on gas oil: 105.94 USD/MWh (produced). This price is valid for production up to 30 MW. If the production on natural gas exceeds 30 MW, the extra gas consumption costs 242.33 US\$/MWh.

#### 4.2.6. CO<sub>2</sub>-quotas

There is a  $CO_2$  emission tax for heat production on boilers with a capacity larger than 20 MW. Næstved has the following "free" quotas: Central Åderupvej 265 tons  $CO_2$ , Central Kanalvej 741 tons  $CO_2$ . The boilers in the other plants in Næstved are too small to pay a  $CO_2$ -tax.

If these quotas are exceeded, the extra cost on the production (gas or oil) is 10.17 USD/ton CO<sub>2</sub>.

#### 4.2.7. Measurements

As previously mentioned 5-minutes data were collected for this project. Three 3-week periods were selected in 2004 representing a winter-, a spring - and a summer situation. However, for financial reasons we will only use data from the winter period January 19 – February 5, 2004 in this work.

In addition to the 5-minutes values, hourly values from the same period were collected from the 35 buildings in the Parkvej area. For simulation purposes the hourly values were interpolated to obtain 5-minutes values. Data from six buildings, including the largest consumer, were collected with 5-minutes interval (in all 41 buildings).

Data available from the consumers are: Primary supply and return temperatures, and flows. From this information the heat demand was calculated. In case of indirect connections, no information was available on the heat exchanger size or the secondary temperatures.

From the SCADA system, 70 values were collected, including heat production, flows, pressures and electrical load of the pumps (or the pump speed).

#### 4.3. Jyväskylä District Heating System

#### 4.3.1. Structural Information

Jyväskylä city in Finland has a district heating network with 343 MW<sub>th</sub> maximum heat demand and 954 GWh of annual consumption. The total length of the DH-pipeline is 290 km. The maximum demand of electricity is 232 MW<sub>e</sub> and the annual consumption is 971 GWh. In total 2387 consumers (1925 residential building, 157 industrial buildings and 305 other) with the total volume of 19752 m<sup>3</sup> are connected to the DH-system. The connection rate is 95 % (79000) of the total amount of 81000 inhabitants in Jyväskylä.

In addition a steel tank heat storage of 7000 m<sup>3</sup> with the heat capacity of 300 MWh and the thermal effect of 25 MW is connected to the DH-system in Savela power plant. The heat storage is connected direct without a heat exchanger to the DH-system: DH-water water flows through round shape radial diffusers into/from the storage when charging/discharging.

#### 4.3.2. Economic Data

Heat-only boilers (HOB) are assumed to be run at load, based on simulation without any DSM activities, at each start-up (heating up and cooling off without feeding the district heating network). The boiler efficiency is taken as 85 %.



Figure 4-3. District heating network and data collection buildings in Jyväslylä

The fuel of the heat-only boilers is heavy fuel oil (HFO), the current price of which is about 36.5 US\$/MWh (excluding VAT). The fuel for Rauhalahti CHP plant and Savela HOB B is milled peat, the price of which is about 15.7 US\$/MWh. Process steam for paper mill Kangas is taken out from intermediate pressure of the turbine in Rauhalahti. A part of the process steam in Rauhalahti can also be produced in a separate HFO fired boiler. The increased DH-output of 20 % can be received from the Rauhalahti CHP plant. The boiler efficiency of the CHP plant is assumed to be 90 % and the power to heat ratio is 0.45. The heating capacity data is presented in prioritised order in Table 4-2. The temperature of outgoing DH water has a maximum of 115 °C in winter and a minimum 75 °C in summer.

| Unit                  | Heat Output | Electricity output | Fuel           | Notice       |
|-----------------------|-------------|--------------------|----------------|--------------|
|                       |             |                    |                |              |
| Rauhalahti CHP        | 140         | 87                 | milled peat    |              |
| Savela boiler B       | 25          |                    | milled peat    |              |
| Savela boiler A1+A2   | 2x40        |                    | heavy fuel oil | These can be |
| Kortepohja boiler     | 3x11        |                    | heavy fuel oil | started also |
|                       |             |                    | -              | in reversed  |
|                       |             |                    |                | order        |
| Varikko boiler        | 30          |                    | heavy fuel oil |              |
| Nisula boiler 1 and 2 | 40+20       |                    | heavy fuel oil |              |
| Kuokkala boiler       | 40          |                    | heavy fuel oil |              |
| Savela CHP            | 62          | 28                 | heavy fuel oil |              |

Table 4-2. Merritt order of production units at Jyväskyla

#### 4.3.3. Measurement Data

From measurements within the system it has been shown that the total heat demand variation is as presented in Figure 4-4. The Production is covered first by milled peat and after that by heavy fuel

oil. Maximum heat was 343 MW in 2002 and the corresponding total heat demand was 954 GWh. The maximum electricity production was 232 MW and the electricity energy demand 971 GWh as shown in Figure 4-5.



Figure 4-4. Heat demand and heat production by milled peat and heavy fuel oil in Jyväskylä.



Figure 4-5. Electricity demand in Jyväskylä in 2002.

The described data was collected in 31 building (Figure 4-3) located in the map of Jyväskylä 1.6.2003 - 31.5.2004 and in addition in two buildings of the Governmental Centre and Pensioners' Day Centre in 2002. At all of the buildings measured in 2003 - 2004 the heat consumption, the electricity and the household water were collected on an hourly basis.

The corresponding data of the Jyväskylä DH-network is presented in Table 4-3.

| Size  | Diameter | Total length of | Volume of                  |
|-------|----------|-----------------|----------------------------|
| DN    | [mm]     | pipeline [m]    | pipeline [m <sup>3</sup> ] |
| 70    | 70.3     | 3362.5          | 13.05                      |
| 80    | 82.5     | 1721.4          | 9.20                       |
| 100   | 107.1    | 6476.0          | 58.33                      |
| 125   | 132.5    | 5822.5          | 80.27                      |
| 150   | 160.3    | 12830.4         | 258.89                     |
| 200   | 210.1    | 21585.5         | 748.21                     |
| 250   | 263.0    | 949.7           | 51.58                      |
| 300   | 312.7    | 13562.0         | 1041.33                    |
| 350   | 345.0    | 5028.4          | 469.98                     |
| 400   | 393.8    | 8055.0          | 980.90                     |
| 450   | 460.0    | 1128.5          | 187.51                     |
| 600   | 593.6    | 4511.5          | 1248.29                    |
| Total |          | 85033.4         | 5147.54                    |

Table 4-3. District heating pipelines more than 70 mm in Jyväskylä.

The distance between Rauhanlahti and Jyväskyä City is about 5 km. 90 % of the pipeline has a diameter of DN600. The volume of the supply pipeline is about 2500 m<sup>3</sup> including all branches with a diameter of more than DN70. Using a temperature lift of 15 °C in order to load this pipeline system a heat quantity of additionally 42.5 MWh could be produced during 2 hours.

# 5. Model based Evaluation of DHS and DSM

In order to evaluate the economic and ecological effects of dynamic heat storage in the network system and the effects of demand side management different models of the Danish district heating system of Næstved and the Finnish district heating system of the city Jyväskylä have been elaborated. To determine the effects of dynamic heat storage models with respect to simulation purposes have been developed. In order to find stable results within an acceptable time and to some of these models have been aggregated.

The following chapter describes the course of the modelling and characterises the different models used to generate information about ecological and economic effects of DHS and DSM.

#### 5.1. DHS evaluation of the Oberhausen DH-system

#### 5.1.1. Modelling of the Oberhausen DH-system

Since the Oberhausen DH-system owned by the energy supply company EVO has been already modelled within the former IEA project "Simple Models of operational Optimisation" in this chapter only a short overview over the main characteristics of this DH-system will be given.

The EVO-network model of the subsystem "Oberhausen" (see Figure 4-1) consists of 2380 pipes, 1000 consumers, 2205 nodes and 176 loops. For the DHS calculations the main production facility called HKWI of Oberhausen has been modelled. This production unit consist of a CHP unit and a heat only boiler (HOB) for peak heat production.

The next table gives an overview over the technical and financial parameters used in the following simulations<sup>6</sup>:

| No. | Parameter                                 | Dimension                               | CHP Unit   | HOB Unit   |
|-----|---|---|------------|------------|
|     |   |   | Oberhausen | Oberhausen |
| 1   | Specific fuel requirement                 | [W <sub>Fuel</sub> /W <sub>Heat</sub> ] | 1.458      | 2.09       |
| 2   | Power ratio                               | [W/W]                                   | 0.35       | -          |
| 3   | Heat ratio                                | [W/W]                                   | 0.55       | 0.9        |
| 3   | Maximal heat capacity                     | [MW]                                    | 90         | 20         |
| 4   | Maximal supply temperature                | [°C]                                    | 115        | 115        |
| 5   | Fuel costs                                | [US\$/MW <sub>fuel</sub> ]              | 145        | 145        |
| 6   | Price for power (base)                    | [US\$/MW <sub>base</sub> ]              | 50.7       |            |
| 7   | Price for power (peak)                    | [US\$/MW <sub>peak</sub> ]              | 59.5       | -          |
| 8   | Specific CO <sub>2</sub> -Emissions (Gas) | $[t_{CO2}/MW_{fuel}]$                   | 0.2        | 0.2        |

Table 5-1 Specifications and restrictions of the production units

The main target of the calculations which will be carried out on the subsystem "Oberhausen" is to evaluate the capacity of the DHS network storage in different load situations. This heat storage should be applied in order to increase the electricity production of the respective production unit. Therefore also the impact towards an optimised production of power is in the center of interest and will be evaluated on basis of the possible financial improvements.

## 5.1.2. Aggregation of the Oberhausen DH-System

Figure 5-1 shows the structure of the simplified network of the subsystem called "Oberhausen". Here only 10 % of the elements are left compared to the detailed network. This aggregated model

<sup>&</sup>lt;sup>6</sup> For the reason of secrecy the parameters have been changed compared to the real parameter.

consists of 146 pipes, 55 consumers, 118 nodes and 32 loops. The main production HKWI is also kept.



Figure 5-1 Aggregtated network of the Subsystem "Oberhausen"

## 5.1.3. DHS-Case Studies of the Oberhausen DH-system

Within this chapter the heat storage capacity of the Oberhausen DH-network should be determined regarding different load situations. For this purpose simulations will be carried out on the aggregated network model of the respective system. The aim is to quantify the maximum heat amount which could be stored into the network with respect to an increased electricity production within the CHP unit located in the centre of the subsystem called "Oberhausen". For this exemplary calculations the subsystem "Sterkrade" can not be regarded since it is operated separately from the "Oberhausen" system.

To evaluate the maximum storage capacity of a network system first of all is to regard the current load situation. Depending on the current heat input and the capacity in terms of maximum heat input and supply temperature of the respective production unit, the possible production level to initiate the loading sequence differs. Due to the heating curve of the production unit, which is depends on the outside temperature, the maximum supply temperature increase to start the loading sequence decreases with increasing heat demand. This effect is shown for the Oberhausen system in the next figure.



Figure 5-2. Possible supply temperature increase to initiate heat storage processes

It can be seen, that up to load demand of 65 MW a maximum supply temperature difference of 35 °C can be applied to load the network. Beyond this level due to the control strategy of HKW I this temperature difference decreases. Reaching 90 MW heat demand there is no space left to initiate heat storage processes. Therefore, within this evaluation only the load situations below 90 MW heat demand will be regarded.

Various simulations on basis of different load situations between heat demands of 40 MW to 80 MW have been carried out in order to determine the heat storage capacity of the Oberhausen DH-network. Here the main results of these simulations will be presented. It is assumed that the maximum temperature increase for all evaluations is 1°C/min.

Figure 5-3 shows the results for a storage process at a supply situation with a heat demand of 60 MW. It can be seen that the maximum storage capacity of the Oberhausen network is 40 MW in this load situation. The storage process is finished after 180 min. This follows to a total heat amount stored in the network of approximately 35 MWh. Regarding Table 5-1 this additional heat production leads to a power production of 23 MWh.

On basis of the fuel price in Table 5-1 this way of producing electricity leads to a electricity price of 50.75 US\$ which is 8.75 US\$ lower than the average price for electricity from the market. Therefore, each MWh electricity produced by own production units on basis of heat storage within the network and sold at market price saves 8.75 US\$. For the regarded time horizon this leads to savings of approximately 200 US\$. Further evaluations regarding the load and capacity of the network and the production units that this level of heat storage strategy can not be applied each day a year. It could be determined, that approximately on 150 days a year in average this level of heat storage could be reached. That means, yearly savings of nearly 31000 US\$ are possible on basis of the average price for power.

Within this context it should be pointed out, that DHS does not need any additional investment. It is based only upon an optimised control strategy of the DH-system.



Figure 5-3 Heat storage capacity at a heat demand of 60MW (storage only in supply line).

Since the this power production with a base load unit is applied during peak load times, it can be assumed that it substitutes peak load production with poor conversion factor. It can be assumed that a peak power production unit generates electricity at conversion factors of 0.2 to 0.25. Regarding the conversion factor of 0.35 used for the Oberhausen CHP in this calculations, the corresponding  $CO_2$ -Emissions can be reduced by 10 % to 15 % per MWh power. Regarding the 10000 MWh fuel which have to fired to produce the power, approximately 2000 t<sub>CO2</sub> will be produced per year in the case of heat storage in the network. If the power will be produced in poor peak power production units about 2250 t<sub>CO2</sub> will be emitted. Therefore, in total 250 t<sub>CO2</sub> can be saved per year. Additionally, due to the improved power production the fuel consumption can be reduced by about 1250 MWh/a.

The situation described above only regards heat storage processes in the supply line of the respective DH-network. If bypasses between supply and return line could be also used in order to use the return line of a DH-network for heat storage processes, the maximum storage capacity could be increased significantly.

The next figure shows the capacity for heat storage processes in the supply and return line of the Oberhausen DH-sytem. In this case the stored heat energy could be increased to a level of approximately 62 MWh. That leads to a possibility of additional power production in the range of 41 MWh per day. Regarding a time horizon of one year and the number of 150 days where the heat storage can be applied, this leads to possible savings of nearly 55.000 US\$ and a  $CO_2$ -reduction of more than 600  $t_{CO2}$ . The fuel consumption could be reduced by almost 2200 MWh gas per year.



Figure 5-4 Heat storage capacity at a heat demand of 60MW (storage in supply and return line)

#### 5.2. DHS Evaluation of the Næstved DH-system

#### 5.2.1. Modelling of Næstved DH-system

The detailed model of the Næstved district heating system has got the following characteristics:

| • | No. of production units:     | 6  |
|---|------------------------------|--|
| • | No. of pumps:                | 10(4 Booster pumps, 6 Pumps at production units) |
| • | No. of valves:               | 6 (2 bypass valves)                              |
| • | No. of customer substations: | 785  |
| • | No. of pipes:                | 1912   |
| • | No. of nodes:                | 1847   |
| • | No. of loops:                | 66   |
|   |                              |  |

The total design heat load of all customer substations included in the model sums up to 128.8 MW. The design heat production of all heat production units is 95 MW. The modelled total length of the pipeline system is 142 km with a summarised volume of 2485  $m^3$ .

Figure 5-5 shows the model structure of the Næstved district heating system. Within the dotted lines two parts of the network are highlighted which are connected by only one pipe to the rest of the system. These situations often lead to bottlenecks which affect the safe supply of customers therefore the proper operation of the whole system. One task of this project is also to find optimised operation strategies in order to avoid these bottleneck situations. DSM and DHS strategies are able to support the optimal operation.



Figure 5-5. Structure of the Næstved DH-network.

In order to model the characteristics of the customer substations measurements in several substations have been carried out. To gain exact data basis five minute values of massflow, supply temperature and return temperature have been collected at 17 representative customers.

The values have been measured over three different time horizons representing the summer, the winter and the intermediate season. With this information it was possible to calculate the time depending heat load and then model the substations.

Figure 5-6 shows as an example the difference of the measured and modelled return temperature of substation 20010105 within the Næstved system. For the modelling a time span from 21.01.04 0:00 until 22.01.04 23:55 has been used. This is the time horizon which will be availed for several DHS calculation since it represents a time with very high massflows in the system and therefore a situation often leading to operational disadvantages.



Figure 5-6. Modelled and measured return temperature of customer substation 26005102 (18.01.04 - 07.02.04).

The return temperatures of all substations are modelled in dependence to the heat load and supply temperature. The corresponding equation is shown below. As this type of model is implemented in the network simulation tool it can not be changed.

$$T_{R}(t) = T_{R0} + \sigma_{L} \cdot \left(1 - \frac{\dot{Q}(t)}{\dot{Q}_{0}}\right) + \sigma_{T} \cdot \left(T_{S0} - T_{S}(t)\right)$$
(22)

It can be seen that the substation is modelled by a linear function with five parameters: The design return temperature  $T_{R0}$ , the design heat load  $\dot{Q}_0$ , the design supply temperature  $T_{V0}$  and the two factors of proportionality which model the dependency of to the supply temperature ( $\sigma_T$ ) and the heat load ( $\sigma_L$ ). For the above mentioned substations theses parameters are as follows:

| • | Żo                    | 997   |
|---|-----------------------|-------|
| • | $T_{S0}$              | 88.82 |
| • | T <sub>R0</sub>       | 57.99 |
| • | $\sigma_{\rm L}$      | 7.74  |
| • | $\sigma_{\mathrm{T}}$ | 0.75  |

The model parameters of the other representative customer substations are presented in the appendix. These 17 substations cover 16.5 % of the total heat demand.

Although quite exact models of 17 representative substations can be supplied still 83.5 % of the total heat demand and a number of 768 substations lack of measurements and therefore a different technique to find reasonable models has to be applied. At most of the production units within the Næstved district heating systems measurement points are located where the massflow, the supply and the return temperature are measured in 5 minute intervals.

These temperatures are representative for the behaviour of a group of consumers supplied by the corresponding production unit. These substations can be modelled applying parameters which have been determined on basis of the measurement points at the production units. However, the return temperatures at the different measurement locations have been compared and there was no significant difference found which should lead to different models for the substations. Figure 5-7 shows this for an example time horizon from 24.11.03 to 26.11.03 where the respective production units were working (only for this time horizon meaningful temperature data of all units could be received).



Figure 5-7. Example of the return temperature at 3 different locations in the network system.

Looking at this return temperature course it makes sense to model all customer substations where no detailed measurements available on basis of the average of the above described temperature pattern. Figure 5-7 shows with the red line the temperature course of the model substation. It can be seen that the model quite good reflects the characteristics of the substations.

The following list illustrates the parameter of the customer substation. As for each substation the nominal load is known, the parameter  $Q_0$  is the corresponding nominal load. For most substations also the average return temperature is known. Therefore, this value could be seen as the design return temperature TR0. With the parameters below the change of the design return temperature due to changing supply temperature and heat demand can be modelled. This model parameters can be applied for each customer substation for which no detailed information on their characteristic behaviour exist.

| $T_{S0}$              | 99.63 |
|-----------------------|-------|
| $\sigma_{\rm L}$      | 4.22  |
| $\sigma_{\mathrm{T}}$ | 0.85  |

All booster pumps within the Næstved DH-system have been modelled with respect to their pressure increase and power demand. The dependencies towards massflow and revolutions are usually modelled with a second order polynom for the pressure increase and a third order polynom for the power demand. The diagrams and corresponding model parameter are shown in the following figures.



Figure 5-8. Booster pump model of Booster pump 1 (Kanalvej).



Figure 5-9. Booster pump model of Booster pump 2 (Aaderupvej)



Figure 5-10. Booster pump model of Booster pump 3 (Aaderupvej)

Within all models it can be seen that the cubic parameters of the power equations are zero.

All production units have been modelled with respect to their maximum heat load. These are:

| • | FASAN | (waste incineration) | 30 MW |
|---|-------|----------------------|-------|
| • | ADV   | (Gas; Light oil)     | 45 MW |
| • | SJV   | (waste incineration) | 20 MW |
| • | KNV   | (Gas, Light oil)     | 40 MW |
| • | NYV   | (Gas)                | 8 MW  |
| • | EJV   | (Gas)                | 12 MW |
| • | HCA   | (Gas)                | 12 MW |
|   |       |                      |       |

The production by waste incineration in FASAN is coupled into the network at the same location as ADV. Therefore, regarding the model, FASAN and ADV could be seen as one combined production unit.

# 5.2.2. Aggregation of the Næstved System

Network simulations in order to evaluate the impact of dynamic heat storage are quite time demanding using the detailed model of the Næstved DH-network. The calculation time exceeds 10 hours for the most simulations. Therefore the detailed model has been simplified based upon the aggregation strategies described in chapter 2.2 or in more detail in the Annex VI IEA Project "Simple models for operational Optimisation". The next figure shows the structure of the aggregated Neastved DH-network. The corresponding aggregation depth is 80 %.



Figure 5-11. Aggregated structure of the Næstved DH-network

This simplified network structure reduced the simulation time to approximately 1/10 of the calculation time for the detailed network. The corresponding number of elements are as follows:

| No. of production units:     | 6  |
|------------------------------|--|
| No. of pumps:                | 10(4 Booster pumps, 6 Pumps at production units) |
| No. of valves:               | 6 (2 bypass valves)                              |
| No. of customer substations: | 128  |
| No. of pipes:                | 328  |
| No. of nodes:                | 303  |
| No. of loops:                | 26   |
|                              |  |

# 5.2.3. DHS-Case Studies of the Næstved system

In order to provide information what influence DHS has on the complete Næstved system simulation with the district heat simulation module of BoFiT have been carried out. In order to avoid time demanding dynamic calculations the aggregated model of the Næstved district heating network has been applied. This also makes the evaluation of several different scenarios possible which should be regarded with respect to positive impacts of DHS.

At the location of the production unit Aaderupvej heat can be coupled into the DH-network from the waste incineration plant FASAN and from gas or oil fired heat boilers. The heat produced at FASAN is less cost intensive than the heat from the fuel fired heat boilers. Sometimes it happens that the waste incineration plant has to stop the heat production and as a result the heat has to be produced from gas or oil. Due to  $CO_2$ -taxes (see chapter 4.2.6) and because of the higher fuel prices (chapter 4.2.5) this situation leads to negative effects on the overall operating costs.

Therefore, dynamic simulations have been carried out in order to determine the time span DHS can buffer a production failure of FASAN. The following different scenarios should be presented in the following:

- A production stop without network storage to buffer the failure.
- A production stop without any chance to load the network before the failure.
- A production stop with a warning time of 6 hours before the production fails out.
- A production stop with a warning time of 24 hours before the production fails out.

In all cases a supply situation from 21.01.2004 00:00 to 22.01.2004 23:45 has been regarded. This was a situation within the year 2004 where a maximum heat load was demanded. The simulation was carried out in 15 minute time steps.

The following diagram shows the regarded time horizon from 21.01.04 to 23.01.04. In this period ADV/FASAN covered a heat demand of approximately 1/3 of the total heat demand.



Figure 5-12. Measured heat input of the production units within the time horizon from 21.01.04 to 23.01.04.

The exemplary production failure at ADV/FASAN should be covered as long as possible by the heat stored in the network and only if this heat does not fulfil the heat requirements of the customers additional heat should be produced by more expensive production facilities which usually work as peak production units and which lead to additional costs due to more expensive fuel and conversion techniques. This situation stands for all load situations in which low cost base

heat production has to be covered by high cost peak heat production. E.g. biomass, waste heat production or heat supply based on low cost purchase contracts.

The failure could be an emergency breakdown of the respective production unit without any time prior the failure to apply any strategies to overcome an increase of the operational costs or an periodic failure (e.g. maintenance, revision of production unit) which gives the possibility to load the network storage in order to reduce the level of increasing production costs.

The following chapter discusses these different situations with respect to varying load situation in the simulation horizon described above. Figure 5-13 shows the course of the produced heat at the Næstved production units if no heat stored in the network could be used in order to decrease the peak demand. It is assumed that the failure has to be covered ultimately applying production unit KNV. All other facilities are operated without any change.



Figure 5-13. Heat input of the production without heat storage (Case 0).

From the model based calculation it can be seen that parallel to the failure of ADV/FASAB a correspondingly high increase of the heat production at KNV occurs. Since the low cost waste heat production is substituted by high cost heat production from gas or oil higher overall production costs can be assumed. The effect on the operational costs and CO2-emissions will be discussed in more detail at the end of this chapter.



Figure 5-14. Heat input of the production with heat storage and without loading prior the failure (Case 1).

Figure 5-14 shows the situation if the heat stored in the network could be used in order to decrease the peak demand at KNV. As for all simulations carried out in this context, except of ADV/FASAN and KNV the heat input is constant.

In this case no manually initiated loading of the network took place. Therefore, this simulation represents a situation without any warning time prior the failure of any production unit.

The loading sequence between 2:00 and 5:00 o'clock on the 21st occurs due to an uncontrolled overproduction. However, it could be shown that there is an effect on the system since at the time of the failure the heat stored enabled an decrease of the overall peak production. Compared to Figure 5-13 a maximum reduction of the peak heat production of approximately 4.5 MW are possible. It is likely that this also leads to decreasing operational costs for the respective time horizon.



Figure 5-15. Manually initiated DHS sequences - the two case studies.

As next, the influence of a DHS-network loading sequence before the failure should be regarded which represents a production breakdown for maintenance etc.. As already described the loading sequence is initiated by an increase of the supply temperature at one production unit. It is assumed that the ADV/FASAN plant is applied to load the network on a low waste heat cost level. However, this storage procedure could be initiated at each production unit in progress. One constraint is that the heat production for network loading should be less expensive than the heat of the peak heat production unit applied to cover the failure of any other supplier. Otherwise the manually loading procedure does not lead to decreasing production costs.

With Case 2 and Case 3 two situations within the time horizon are regarded taking into account the specific load situation at the respective point in time and the corresponding duration before the failure of ADV/FASAN. In both exemplary simulations the DHS is initiated by an temperature lift of 10 °C. Figure 5-16 shows the impact of a network loading sequence 6 hours before the waste heat production at ADV/FASAN fails. It can be seen, that the total heat received from the network after the production failure is increased by approximately 2 MW to a level of 7.5 MW and that the duration of the peak shaving by DHS in the network is longer than compared to the situation represented in Figure 5-14. Based upon this results it can be assumed, that beside of the heat already stored in the network an additionally manual loading of the pipeline system supports the decrease of peak demands.

Case 3 is shown in Figure 5-17. Here a situation is described where the loading procedure was initiated 24 hours before the production failure. It can be seen, that the maximum peak demand after the breakdown covered by heat storage is approximately 1.5 MW lower compared to Case 2. This is due to the fact, that the heat stored into the network has been already unloaded between 21.1.04 22:00 and 22.1.04 05:00 and is therefore not available to buffer the failure. It is difficult to avoid this effect since each change in heat input or heat demand leads to change of the storage

state of the network. One safe strategy to get around this situation is to start the loading procedure close to the shut down procedure.



Figure 5-16. Initiation of DHS 6 hours prior the production failure of ADV/FASAN (Case 2).

Another effect can also be studied quite good regarding Figure 5-16 and Figure 5-17. It can be seen that the duration of the storage process in Case 3 is much longer than the loading procedure in Case 2. This is due to the fact that in Case 3 the heat storage process started at a situation with high heat demand (high massflows) and during the loading procedure the heat demand (massflow) decreased. Since DHS processes are finished faster in situations with high heat demand (massflows) a decreasing massflow leads to a extension of the loading procedure. In Case 2 it is exactly the opposite situation. Therefore, the storage process was finished quite quickly.



Figure 5-17. Initiation of DHS 24 hours prior the production failure of ADV/FASAN (Case 3).

The figures above mainly describe technical impacts of dynamic heat storage processes. As next a short overview on the financial and ecological effects will be given. The next table shows the costs for the different test cases Case 0 to Case 3. It can be seen that compared to a situation without any DHS the financial improvements could be 1 % to 1.3 % due to the test situations. As already described above the best strategy is to initiate the loading procedure close to production failure (Case 2).

| Case | Costs [US\$] | Savings [US\$] | Savings [%] |
|------|--------------|----------------|-------------|
| 0    | 305864       | 0              | 0,00%       |
| 1    | 302726       | 3138           | 1,03%       |
| 2    | 301808       | 4056           | 1,33%       |
| 3    | 302783       | 3081           | 1,01%       |

Table 5-2 Savings due to the exemplary DHS simulations (total costs for 48 hours).

Within this context it is essential to point out that the simulations carried out just represent a dynamic heat storage in the Næstved DH-system without taking into accout any optimisation potential in order to apply the optimal DHS strategy to buffer the production failure. It is very likely that there is an additional space for improvement.

The next table describes the possible reduction of CO2-Emissions regarding the simulations carried out here.

| Case | CO <sub>2</sub> -Emission [t <sub>CO2</sub> ] | CO <sub>2</sub> -Reduction [t <sub>CO2</sub> ] | CO <sub>2</sub> -Reduction [%] |
|------|---|--|--------------------------------|
| 0    | 438   | 0  | 0                              |
| 1    | 436   | 1,84   | 0,42%                          |
| 2    | 436   | 2,16   | 0,49%                          |
| 3    | 437   | 1,70   | 0,39%                          |

Table 5-3 Possible Reductions of CO2-Emissions due the exemplary DHS simulations.

Again Case 2 leads to the highest reductions of about 0.5 % relative to the situation without heat storage.

#### 5.3. DHS Evaluation of the Næstved Subsystem Parkvej

#### 5.3.1. Modelling of the Subsystem Parkvej

In order to evaluate the optimal use of DHS as an example the New Parkvej district in Næstved has been evaluated for the period January 21-22, 2004. This system is modelled as five times greater than the real Parkvej system (see Figure 4-2). This corresponds to a heat input and demand of the complete Næstved system.

The DH-network and the customer substations have been moddeled using the simulation platform DHSim. As mentioned in Section 4.2.7 measurement data has been collected on a 5-minutes basis, partly interpolated from hourly values. For the period January 21-22, 2004 the mean load is 31243 MW in the New Parkvej system. Consumer 2001009 is by far the largest consumer, cf. Table 4-1.

DHSim calculates heat loads and primary return temperatures based on measured time series. E.g. a return temperature is calculated depending on a supply temperatures taking into account the measured return and supply temperatures:

$$T'_{r,prim}(t) = T_{r,prim}(t) + \left( \left( \frac{T'_{s,prim}(t)}{T_{s,prim}(t)} \right)^a - 1 \right) \cdot b$$
(23)

In this equation the parameters a and b are constants. Different values are assigned to the constant a when the new supply temperature is either above or below the measured supply temperature. In this way, the return temperature response will be similar to the response of a plate heat exchanger.

In this case study the following figures will be used:

- a = -1, when Ts\_prim(t)\* > Ts\_prim(t),
- a = -3, when Ts\_prim(t)\* <= Ts\_prim(t). (24)

• b = 5.

| °C                                     | R01 week 2 |      |      | R01 week 13 |      |      |
|--|------------|------|------|-------------|------|------|
| Supply temperature from the substation | 80         | 90   | 100  | 80          | 90   | 100  |
| Return temperature                     | 56.3       | 54.1 | 53.2 | 51.0        | 49.5 | 48.7 |
| Cooling                                | 23.7       | 35.9 | 46.8 | 29.0        | 40.5 | 51.3 |

All connected buildings will influence the return temperature at the plant, but to give an impression of the influence of the supply temperature, Table 5-4 shows the return temperature at the plant as a function of different supply temperatures.

Table 5-4. Test of DHSim option –e. Return temperature and cooling at the substation R01 Madumvej in Roedovre as a function of supply temperature.

It is assumed that there is one circulation pump located at the entrance to New Parkvej. Its' pumping curve is shown in Figure 5-18 and the efficiency at 1450 rpm in Figure 5-19. The five subsystems are connected at the plant as a "star", i.e. the differential pressure is the same in all five subsystems and the total flow is five times the flow in one subsystem. The pumping costs are calculated assuming a differential pressure of 4 m w.g. at the "critical" consumer and the pumping and efficiency curves shown in Figure 5-18 and Figure 5-19. The optimisation is carried out with the Matlab 6.5 function fmincon. It is assumed that the first and the last supply temperature of the optimisation horizon must be the same and that the maximum change of the supply temperature is  $2 \degree C$  per hour.

The target of this optimisation is the minimisation of operational costs. Costs assumptions are stated in *Section 4.1.5*. It is assumed that the production takes place only on the gas boilers. In this respect it is important to keep the production lower than 30 MW as the gas price increases very much above 30 MW due to the contract between Næstved and the Danish National gas company. However, for comparison we will also find the optimum supply temperature curve when the heat comes from the waste incineration plant. In the following cases we will not take the CO<sub>2</sub> emission tax into consideration.







Figure 5-19. Efficiency of the pump wheel at 1450 rpm. Hypothetical pump at the entrance to New Parkvej.

The dynamic heat loss is calculated as the amount of heat supplied to New Parkvej minus the heat consumption in the buildings.

5.3.2. DHS Evaluations of the Subsystem Parkvej

• Case 1

In case 1 the heat production from the waste incineration plant is regarded. The low fuel costs are 50 USD/MWh

The following table shows the dynamic heat loss, the energy for pumping and the production. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>7</sup>.

The heat loss is 2.9 % of the production and the operational costs 3.3 % of the total costs.

|                         | 90 °C  | OPTIMUM | Measured | 75 °C  |
|-------------------------|--------|---------|----------|--------|
| Dynamic Heat Loss [MWh] | 47.94  | 44.60   | 43.64    | 41.63  |
| Pumping [MWh]           | 1.19   | 1.69    | 2.28     | 3.00   |
| Production [MWh]        | 1547.6 | 1544.3  | 1543.3   | 1541.3 |
| Costs Buildings [USD]   | 75157  | 75157   | 75157    | 75157  |
| Costs Operation [USD]   | 2636   | 2566    | 2635     | 2675   |
| Total costs [USD]       | 77793  | 77723   | 77792    | 77833  |

Table 5-5 Parkvej Operational costs for 48 hours.

The following figure shows the optimum supply temperature and the corresponding return temperature as well as the total heat load in the buildings in MW. The measured supply temperature is shown in pink.



Figure 5-20. Waste heat. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

• Case 2

In case 2 the heat production from the natural gas boiler is regarded. The low fuel costs are 80 USD/MWh.

The following table shows the dynamic heat loss, the energy for pumping and the production. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>8</sup>.

<sup>&</sup>lt;sup>7</sup>  $P_{\text{fuel}} = 50.12 \text{ USD/MWh}, P_{\text{power}} = 196.45 \text{ USD/MWh}, Q_{\text{buildings}} = 1499.7 \text{ MWh}.$  Mean load: 31.05 MW.

 $<sup>^{8}</sup>$  P<sub>fuel</sub> = 80 USD/MWh, P<sub>power</sub> = 196.45 USD/MWh, Q<sub>buildings</sub> = 1499.7 MWh.

|                         | OPTIMUM | Measured |
|-------------------------|---------|----------|
| Dynamic Heat Loss [MWh] | 43.08   | 43.64    |
| Pumping [MWh]           | 2.14    | 2.28     |
| Production [MWh]        | 1542.8  | 1543.3   |
| Costs Buildings [USD]   | 120053  | 120053   |
| Costs Operation [USD]   | 3868    | 3941     |
| Total costs [USD]       | 123921  | 123994   |

Table 5-6. Parkvej. Operational costs for 48 hours.



Figure 5-21. Low gas price. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

# • Case 3

In case 3 the heat production from the natural gas boiler is regarded. The high fuel costs are 263 USD/MWh.

The following table shows the dynamic heat loss, the energy for pumping and the production. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>9</sup>.

|                         | OPTIMUM | Measured |
|-------------------------|---------|----------|
| Dynamic Heat Loss [MWh] | 38.94   | 43.64    |
| Pumping [MWh]           | 4.59    | 2.28     |
| Production [MWh]        | 1538.6  | 1543.3   |
| Costs Buildings [USD]   | 394655  | 394655   |
| Costs Operation [USD]   | 11148   | 11932    |
| Total costs [USD]       | 405803  | 406587   |

Table 5-7. Parkvej. Operational costs for 48 hours.

 $<sup>^9</sup>$   $P_{\rm fuel}$  = 263 USD/MWh,  $P_{\rm power}$  = 196.45 USD/MWh,  $Q_{\rm buildings}$  = 1499.7 MWh.



Figure 5-22. High gas price. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

## • Case 4

In case 4 the heat production from the natural gas boiler is regarded. The fuel costs are variable within a range of 80 USD/MWh for load < 30 MW and 263 USD/MWh for load > 30 MW.

The following table shows the dynamic heat loss, the energy for pumping and the production. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>10</sup>.

|                         | OPTIMUM | Measured |
|-------------------------|---------|----------|
| Dynamic Heat Loss [MWh] | 39.00   | 43.64    |
| Pumping [MWh]           | 4.94    | 2.28     |
| Production [MWh]        | 1538.7  | 1543.3   |
| Costs Buildings [USD]   | 141255  | 142282   |
| Costs Operation [USD]   | 4655    | 4594     |
| Total costs [USD]       | 145910  | 146876   |

Table 5-8. Parkvej. Operational costs for 48 hours.



Figure 5-23. Variable gas price. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

 $<sup>^{10}</sup>$  P<sub>fuel</sub> varaible, P<sub>power</sub> = 196.45 USD/MWh, Q<sub>buildings</sub> = 1499.7 MWh.

It appears from Table 5-7, that the operational costs are higher in the optimum case than when the measured supply temperature is used, primarily due to the bigger flow at the lower supply temperature. However, the total costs are lower when the optimum supply temperature curve is used. This has been obtained by storing heat in the network before the maximum loads occur. Although Næstved DH company apply a boosting of the supply temperature of approximately 3 K, in the optimum solution the boosting is slightly bigger and it occurs earlier.

• Case 5

In case 5 the heat production from the natural gas boiler is regarded. The fuel costs are variable within a range of 80 USD/MWh for load < 30 MW and 263 USD/MWh for load > 30 MW. A level of 20 % peak shaving due to DSM application is regarded.

In case 5 and 6, we will discuss the influence of DSM applied in the buildings. However, due to the lack of resources in the project it has not been possible to model the buildings in Parkvej and instead a simple form of DSM will be applied to see the effect on the operational costs. First we will consider the case with 20% peak reduction in all buildings, i.e. the peaks as well as the "valleys" are even out by 20%, but the mean value of the heat load is preserved. This approach is illustrated in Figure 5-25 for one of the buildings in Parkvej. It should be pointed out that this simple way of changing the heat load does not take into account the control system in building and the heat capacity of the building.



Figure 5-24. Heat loads at consumer 20010009 for 0 (blue), 20 (green) and 80 % (red) peak shaving (DSM).

The following table shows the dynamic heat loss, the energy for pumping and the production in case of 20% DSM. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>7</sup>.

|                         | OPTIMUM | Measured |
|-------------------------|---------|----------|
| Dynamic Heat Loss [MWh] | 38.60   | 43.65    |
| Pumping [MWh]           | 5.20    | 2.27     |
| Production [MWh]        | 1538.3  | 1543.3   |
| Costs Buildings [USD]   | 139786  | 140790   |
| Costs Operation [USD]   | 4693    | 4576     |
| Total costs [USD]       | 144479  | 145367   |

Table 5-9. Parkvej. Operational costs for 48 hours.



Figure 5-25. Variable gas price and 20% DSM. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

• Case 6

In case 6 the heat production from the natural gas boiler is regarded. The fuel costs are variable within a range of 80 USD/MWh for load < 30 MW and 263 USD/MWh for load > 30 MW. A level of 80 % peak shaving due to DSM application is regarded.

The following table shows the dynamic heat loss, the energy for pumping and the production in case of 80% DSM. It also shows the costs of heating the buildings, the operational costs and the total costs for operation the DH system for 48 hours<sup>7</sup>.

|                         | OPTIMUM | Measured |
|-------------------------|---------|----------|
| Dynamic Heat Loss [MWh] | 38.61   | 43.63    |
| Pumping [MWh]           | 5.24    | 2.24     |
| Production [MWh]        | 1538.3  | 1543.3   |
| Costs Buildings [USD]   | 137467  | 138336   |
| Costs Operation [USD]   | 4705    | 4579     |
| Total costs [USD]       | 142172  | 142915   |

Table 5-10. Parkvej. Operational costs for 48 hours.



Figure 5-26. Variable gas price and 80% DSM. Optimum supply temperature (red), the corresponding return temperature (blue) and the total heat load in the buildings (green). The pink curve is the measured supply temperature.

It appears from Figure 5-25 and Figure 5-26 that the optimum supply temperature curve is lower than the measured one when DSM is applied. It also appears that there is less need to boost the supply temperature.

Summarising the results from the optimisation calculations of the New Parkvej system, it can be seen how the fuel price influences the optimum temperature level. For low fuel prices the optimum supply temperature is higher than for expensive fuel costs, because the heat loss is less important.

For variable fuel price it is important to reduce the heat load below 30 MW. Therefore with the optimum supply temperature curve the supply temperature goes up before the load increases. However, the possibility to change the heat load in the buildings is rather limited as only the flow and return temperature is affected by the new supply temperature at the building.

When DSM is applied, i.e. 20 and 80% peak shaving, it is possible to reduce the heat load to some extent below 30 MW. It should be noticed here that the mean load is 31.2 MW. Had the mean load been below 30 MW, the possibility to reduce the load below 30 MW would have been even better, thus increasing the savings in operational costs.

The savings from optimising the operation by using DHS are summarised as follows:

- Savings for constant fuel costs: < 0.2% of total costs, 1.8-6.5% of operational costs.
- Savings for variable fuel costs: +0.6% of total costs, -1.3% of operational costs (due to the bigger flow).
- Savings by applying 20-80% DSM: 1% 2.6% of total costs, compared with no DSM

## 5.4. DHS Model of the Jyväskylä System

## 5.4.1. Modelling of the Jyväskylä DH-System

Also for the Jyväskylä DH-system a model has been implemented in BoFiT. The different steps of the modelling procedure are the same compared to the modelling of the DH-system of Næstved. Therefore, they will not be explained in detail again.

The model consists of the following number of elements:

| • No. of production units:     | 4  |
|--------------------------------|--|
| • No. of pumps:                | 7 (3 Booster pumps, 4 Pumps at production units) |
| • No. of valves:               | 3 (1 bypass valves)                              |
| • No. of customer substations: | 330  |
| • No. of pipes:                | 764  |
| • No. of nodes:                | 723  |
| • No. of loops:                | 40   |

The following diagram shows the corresponding network structure.



Figure 5-27. Structure of the detailed Jyväskylä DH-network.

# 5.4.2. Aggregation of the Jyväskylä DH-system

In order to reduce the duration of the simulation and to enable DHS and DSM calculation strategies the Jyväskylä district heating network has been aggregated to a aggregation depth of 80 %. That means the aggregated model consists of a 80 % less elements that the detailed model which increases the duration of simulations by a factor of 10.

The aggregated model has the following number of elements:

| • | No. of production units:     | 4  |
|---|------------------------------|--|
| • | No. of pumps:                | 7 (3 Booster pumps, 4 Pumps at production units) |
| • | No. of valves:               | 3 (1 bypass valves)                              |
| • | No. of customer substations: | 69   |
| • | No. of pipes:                | 168  |
| • | No. of nodes:                | 153  |
| • | No. of loops:                | 14   |
|   |                              |  |

The structure of the network is described in Figure 5-28. This model is used in order to evaluate the impact of DSM especially in a situation where a lot of customers are regarded as possible DSM candidates (see chapter 5.5.5). Additionally, DHS calculations were carried out on basis of this model in order to evaluate the possibility to cut the morning peak.

## 5.4.3. DHS Evaluation of the Jyväskylä DH-system

In Figure 5-29 the modelling results of this peak shaving are presented. It has been determined that the this temperature of 15 °C lift only leads to a small amount of electricity losses in the CHP plant. As maximum temperature change a value of 1 °C / 6 minutes is regarded which is a quite common temperature changing coefficient to ensure that the thermal stress in the pipeline walls does not became too high. Utilising a temperature lift of 15 °C in 90 minutes about 42.5 MWh heat can be loaded into the pipeline system. Here the big major pipeline of DN600 with a length of 5 km leading from Rauhanlahti to Jyväskylä city and the connected branches with more than DN300 support the maximum heat storage capacity of the network. It takes about three additional hours until the loading sequence is finished. The heat storage discharges itself because of automatic valve control in the houses. This discharging process is dominated by the characteristically behaviour of the customers. Therefore, only the charging process can be controlled by the energy supplier.



Figure 5-28. Structure of the aggregated Jyväskylä district heating network.

Based on data of the heat consumption within the year 2002 it could be determined that it is possible to charge the pipeline system approximately 130 times. During winter time the network and the production units utilisation are at a maximum and there is no space for the application of heat storage processes. The total charged heat in 2002 could then be summarised to 5400 MWh for cutting the peak loads in the morning over a period up to 4-5 hours. The total cost savings were about 100000 US\$ a year and heavy oil was saved in a range of 510 t/a.



Figure 5-29. Modelling results of peak shaving in the morning in the Jyväskylä system.

If the base load production is realised using peat 6220 MWh/a (2220 t/a) of peat have to be fired.. Since peat has a higher emission factor compared to heavy oil, the total  $CO_2$  emission increased 741 t/a.

#### 5.5. DSM Model of the Jyväskylä System

#### 5.5.1. Case Study of Governmental Centre in Jyväskylä

There were three case study buildings in the project, where the DSM demonstrations were carried out. The Jyväskylä governmental building located in the city centre has 6 floors and the total floor area is 5 940 m<sup>2</sup>, where the heated floor area is 5 140 m<sup>2</sup>.



Figure 5-30. Response of the Governmental Centre building for DSM in Jyväskylä, when ventilation is half on or off.

The building has a concrete body covered by bricks and the total volume is 19380 m<sup>3</sup>. The window area is about 30 % and the door area about 0.5 % of the wall area. The total heat consumption (corrected by degree days) was 713.1 MWh in 2000 and 867.8 MWh in 2001. The DH-substations' heat exchanger consists of three parts with the capacities: heating 465 kW, air conditioning 1280 kW and domestic hot water 580 kW.

## 5.5.2. Time Constant of the Governmental Centre

As shown in Figure 5-30 the lift period takes about the same time as the cut period. The indoor temperature decreases by 2 °C (21 ==> 19 °C) during 4 hours, if ventilation is on and outdoor temperature is -28 °C. If ventilation is shut off, it takes 5:50 hours to reach 2 °C lower indoor temperature. The time constant  $\tau$  of the building is 135 hours as long as ventilation is shut off and 92 hours if the ventilation is operating.

## 5.5.3. Comparison of measured Data and the Building Model

Water flow and heat demand at the Governmental Centre divided in radiator heating circuit and HVAC heating is presented in Figure 5-31 and Figure 5-32. The functions are approximated by a polynomial of 4th degree. The functions are valid up to +17 °C of outdoor temperature, if the heating will be cut off and only hot domestic water demand will remain.

In Figure 5-33 the heat power at the Governmental Centre is presented as a function of the outdoor temperature in four different ways. The first curve is calculated based on the building model. The second curve is based on the fitted function of Figure 5-32. The third curve is the measured heat power through a heat meter at the consumer. The fourth curve is calculated based on DH-outgoing and return temperatures and water flow of Figure 5-31. The best response to measured heat power data exists for the building model.



Figure 5-31. Water flow at Governmental Centre as a function of outdoor temperature.



Figure 5-32. Heat demand at the consumer as a function of the outdoor temperature.

#### 5.5.4. DSM Tests in the Case Study Building

DSM control is carried out in Jyväskylä by using multiple temperature control curve applications, where different curves are activated by demand. The characteristics added to the room heating control for the DSM application have the same shape as the normal (existing) curve but the slopes of curves are different. The DSM curves are located below the normal curve but for the preheating and heating up procedure there is a curve above the normal level.

During the transient test of the Jyväskylä office building in 2002 the cut off period of heating and ventilation (during night time) was seven hours and the average reduction of the indoor temperature of eight measurements within the building was 2 °C. Based on several temperature control measurements the lowest pre-programmed control curve (-60 %) was applied. What concerns the ventilation the temperature of intake air heating remains almost untouched as the temperature compensation of the ventilation air is reduced by 2 °C for the DSM period.

The load cuts were the highest at the radiator heating network. It takes time before the network is cooled down to the desired DSM flow temperature level. When the circulation water reaches this DSM temperature level, the heating load starts to increase up to the load level defined by any current DSM temperature setting. Hot tap water was not included in DSM. The load of intake air heating is large but the thermal capacity of the ventilation intake air heating is small compared to the large space heating systems. As a temperature change of the ventilation air can be felt immediate, the DSM-control measures of the ventilation have to be very sensitive while the building is in a normal use. The only way to keep the heat demand of intake air low during the DSM operations is to reduce the air flow temperatures slightly (by 1...2 °C).



Figure 5-33. Heat power response in 4 ways as a function of time (outdoor temperature) in Governmental Centre, January, 2002.

If the maximum temperature of the radiators remain above 40 °C it still reduces the draft at the windows and maintains a comfortable feeling even when the radiator is touched by hand. The maximum DSM load reduction level at the supply temperature was limited to -60% of the normal load level as shown in Figure 5-34. At the beginning of the DSM period this temperature reduction leads to maximum load reduction of -80% for a period of 30 minutes and after following 30 minutes the load reduction recovers to a level of -30% to -20% compared to the usual heating load.

By increasing the flow temperature to reach a 20 % higher heating capacity this high increase of heating is effective only for a short period (< 1 hour) and for the rest of the preheating period (3 hours) there is only a +5 % higher heating load compared to the normal load due to the thermostatic valves. The preheating is important in rooms where the risk of freezing is high, e.g. entry wind boxes. The radiators of entry wind boxes are usually designed without thermostatic valves. Here at early morning and when the doors stay closed the preheating of the building material is effective.



Figure 5-34. Loads of ventilation and radiator heating during DSM operation in winter 2003.

The ventilation system does not start to compensate the reduced heating if the DSM period is short enough compared to the pre-set temperature reduction of in-blowing air (-2  $^{\circ}$ C of the normal).

The analysis of the temperature and load measurements of the Governmental Center gives a reason to reduce the length of the preheating period in order to maximise the network temperature just before the DSM cut off. If a usual night time set down of the flow temperature is used directly before the short preheating, the flow rate in the whole radiator network stays high during the preheating and a maximum heat amount can be accumulated in a short heat storage period. The flow rate at the entry wind boxes must be measured or guaranteed by temperature measurements during the DSM cut off period if the preheating is minimised.



Figure 5-35. Impact of DSM in Governmental Centre to thermal power compared to periods without DSM as a function of outdoor temperature.

The impact of DSM to the thermal power demand of the Governmental Centre is presented in Figure 5-35. The half an hour thermal power marks are printed as a function of the outdoor temperature for the cases that DSM is applied or not. Regression lines represent the DSM tendency

as a function of outdoor temperature. DSM cuts thermal power demand by about 15 % at maximum and there is no DSM if the outdoor temperature is higher than +3 °C.

#### 5.5.5. DSM Calculation and Results

In a case study demand side management is applied during 3 hours in the morning from 6:00 to 9:00 am, each time it could be avoided to start or shut down the HOB. The post-heating period follows, when the cut energy was produced to balance the house demands. The DEM model determined 131 breakdowns of boilers which could be avoided as shown in Table 5-11. The boiler shut downs are presented also in Figure 5-36 shown with minus values and post heating periods are shown with positive values.

| Unit      | Savela | Savela | Kortepohja | Varikko | Nisula | Kuokkala | Total |
|-----------|--------|--------|------------|---------|--------|----------|-------|
| fuel      | peat   | hfo    | hfo        | hfo     | hfo    | hfo      |       |
| Breakdown | 0      | 85     | 1          | 38      | 1      | 6        | 131   |

Table 5-11. Boiler breakdowns when DSM is used in Jyväskylä.

In this case study the starts of heat-only boilers do not cause any additional man-hour costs, because the boilers are started and shut down using remote control. Additionally, the saved pumping energy in the DH-network during the cut period will be used afterwards in the lifting period. The pumping head needed during off peak period is somewhat lower if the district heating network is operated at load conditions where the additional heat is delivered by increasing the flow rate. If the DSM controlled customer is located at the hydraulically most critical point of the network the savings of pumping can be remarkable through the whole heating season.

As there are no additional labour costs, the saving potential of DSM consists of three components:

- 1. The fuel wasted when starting and shutting down the heat-only boilers
- 2. The net profit of back-pressure CHP electricity sales (average 13 US\$/MWh)
- 3. The differences in fuel prices and boiler efficiencies  $(P_{hfo}/\eta_{HOB} P_{peat}/\eta_{CHP})$

Based on simulations with the DEM model in order to evaluate how to use the energy production capacity, the total saving can be summarised to 17000 US\$/a in Jyväskylä case, when DSM is in use. The share of saving in the start-ups and tails of HOB is about 11100 US\$/a. Thus, it means an average saving of 107 US\$ for each of the 160 consumers. This enables a DSM investment of 1100 US\$ per consumer (5%, 15 a).



Figure 5-36. Peak cut and post heating periods in Jyväskylä.

If it is assumed to save an investment of 20 MW HOB (2.35 Million US\$) due to DSM and if this investment is divided on 20 years with 5 % interest, the additional saving will be 188000 US\$/a. Together with maintenance and other fixed cost, it sums up to about 1175 US\$/a per consumer in the Jyväskylä case.

It was estimated that there are so many customers connected to the Jyväskylä system that demand side management could reduce the daily peak demand by 10...20 %. From this basis it can be assumed, how many starts of the heat-only boilers could be annually avoided. A peak cut of 20 % in Jyväskylä means about 160 buildings. Regarding a town building area this figure amounts to 150 - 300 hectares (about 370-740 acres). If the HOB is shut down, a half hour tail heating period was assumed for the boiler for 25 % of the heat load. When the boiler is started up, the pre-heating load is assumed to be a half hour in 25 % load when connected to the network.

# 5.5.6. Summary

Shifting the heat load of a building is based on exploiting the thermal mass of the building and the secondary networks. The research made in two case buildings during winter 2002-2003 shows that the maximum heat load of a massive building (body of concrete) can be temporarily (during 2-3 hours) reduced to a level of 20 - 25 % compared to the average demand. In the studied cases the room temperature was temporarily lowered or raised by maximum 2°C, but this large temperature changes did not occur during the normal test conditions. When this kind of measures are performed in a large number of buildings simultaneously, the total load of a district heating network can be lowered up to 25 %.

The peaks usually occur in the morning and/or in the evening due to simultaneous starting and shut-down sequences of building heating systems, especially in commercial buildings (offices, schools, etc.). These time bounded peaks in typical buildings can be easily shifted by timer controlled DSM measures. A more sophisticated DSM can also include active reducing of certain key customers' loads so that their loads would be high when the other's are low and vice versa. Cutting down the total load in a district heating network can avoid to start peak heat-only boilers during a 24-hour period. However, the same amount of heating energy (or slightly more) needs to be produced as without any DSM measures. This energy can then be produced in a more efficient way than with a heat-only boiler, for example with a combined heat and power (CHP) plant.

Avoiding the starts of heat-only boiler(s) results in direct savings (or profits) for the heat and power producer, which can be categorised in four groups:

- Saving the labour costs related to starting the heat-only boiler(s),
- Saving the fuel that is consumed in the heat-only boiler(s) during start-up and tailing (i.e. when the boiler is off-line, not feeding the district heating network),
- Producing heat with cheaper fuels,
- Producing electricity with the heat load in a back-pressure CHP plant.

If demand side management can be successfully applied, the designed heat demand can be reduced. This results in savings of the investment of primary pipeline systems but may increase the investment of heat exchangers, secondary piping and radiators because the heating and ventilation load peaks during DSM recovery period. The best feasibility of DSM in the whole district heating system including the customer substations can be reached by keeping the use of DSM actions within a limited outdoor temperature range.

# 6. Heat Storage Applications in Partner Countries

Within this chapter the different heat storage applications in the partner countries will be presented. The aim is to show different possibilities of heat storage by heat accumulators, demand side management and dynamic heat storage in the network. On the one hand side information will be given towards the question whether DHS and DSM are already used to improve the operation of the DH-systems or not. On the other hand side this chapter will show if there are significant differences between the storage strategies in the countries participating at this project. Finally, this chapter will add information to the basis for the general discussion presented in the next chapter.

# 6.1. Heat Storage in Denmark

In the 1990s, there was a widespread conversion in Denmark from heat production using oil and coal to natural gas based CHP and biomass-based heat production. As a result of this change there are today in Denmark 285 decentralised CHP plants and 130 decentralised DH plants besides 16 centralised CHP plants. Moreover there are approximately 380 CHP plants and 100 DH plants in the private sector (enterprices and institutions), ENS (2005).

## 6.1.1. Heat Storage in Accumulators

Almost all public CHP plants have a heat storage. These have been built

- to optimise the production from small-scale CHP plants allowing them to produce when the price for electricity is highest during the day
- to optimise production from large extraction CHP plants
- to optimise operation of solid fuel boilers
- to level daily heat load variations
- to serve as pressure maintenance of the system and as a water storage
- to provide the peak hour load on the coldest day, DBDH (2005).

The relative high percentage of electricity production covered by wind mills in Denmark has increased the significance of using heat storages in the overall control of the electrical system.

Most storages are pressureless tanks with direct connection to the network. For the small-scale CHP plants the storage has been designed to store daily production, enabling the plant to produce when the price of electricity is highest (triple tariff).

A few storages are of a more complex type (with temperatures up to 120 °C and indirect connection via pumps and throttle valves), e.g. the three tanks in the Copenhagen.

Figure 6-1 shows the size of 177 storage tanks as a function of maximum electric power.

Most storage tanks are placed close to the production units, however, Berg (1985) investigated the technical and economic applicability of decentralised buffer tanks in existing as well as new district heating systems. Tanks 10 to  $1000 \text{ m}^3$ , placed local in the network, were analysed as an alternative to reinforcement of the pipes in the case of connection of new heat loads to the DH system.


Figure 6-1. Size of 177 heat storages as a function of maximum electrical power. Danish District Heating Association (2005).

#### 6.1.2. Dynamic Heat Storage

The storage tank makes it possible in many cases to avoid starting peak load boilers in the morning. Some DH companies boost the supply temperature in the morning as we have seen in the Parkvej case in Næstved, but most DH companies use the capacity of the storage tank to cover the peak demand in the morning.

The question of applying night set back or not in the buildings has been debated from time to time and most DH companies are not in favour of using night set back. In most cases the building owner has the right to use night set back so the DH company must persuade him not to apply it, or they must use a tariff which punish big load variations and poor cooling of the DH water. Today many DH companies have reached an agreement with the building owners not to start the reheating in the morning at the same time in all buildings.

Due to the morning peak it can be necessary to start peak load boilers (if the storage tank is not big enough) and this fuel (natural gas or light oil) is much more expensive than the base load fuel. In the Copenhagen DH system, the peak load production costs approximately four times the cost of CHP and waste heat production. In order to reduce the morning peaks, the VEKS transmission company applies an incentive tariff, where the connected DH distribution companies receive a bonus for levelling out the daily load variations and a penalty for not doing so. The incentive tariff also include an incentive to lower the return temperature at the substation to VEKS.

Wiuff (1987) investigated theoretically the possibility to apply a flow stop at night or lower supply temperatures at night from the DH plant. Flow stop at night results in annual energy savings of approximately 5% in the network and 4-8% in single family houses and apartment buildings, in offices 20 - 30%. Lower supply temperature at night saved up to 5% in the network and 0-2% in the dwellings. It was concluded that flow stop at night should never be introduced before careful investigations of the system had demonstrated that the system has sufficient capacity and strength. Lower supply temperature at night may normally be introduced without such investigations.

The use of cogenerated heat in greenhouses was is the subject of a major Danish research effort, A/S Samfundsteknik, SAAS Instrument as, Cowiconsult, B. Højlund Rasmussen (1987-1989).

The reports addresses the influence on the operation of a major CHP plant from daily load variations of several greenhouses. Heat storage in the network, the use of storage tanks, the use of

flow limiters at each greenhouse, and DSM by applying different temperature programmes in the greenhouse are discussed as different means of peak shaving at the CHP plant.

#### 6.1.3. Demand Side Management

Greenhouses are atypical consumers with large load variations. On Funen many greenhouses are supplied from the central CHP plant in Odense. Storage tanks could be used to reduce the peak loads, Nielsen (1986). Amsen (1988-1992) investigated the use of DSM (peak shaving) on the energy consumption and the response of pot plants. One strategy for temperature control is based on high night temperatures (22°C) and low day temperatures (14°C) in the greenhouse - in contrast to night set back in dwellings.

Traditionally radiator systems have been oversized to ensure a good cooling of the DH water. However, this means that the radiator system can boost the loads in the building as well as in the DH system by a factor of two or more.

Intelligent control equipment for buildings is on the market. Better control of the heating system can lead to both reduced peak loads and to improved cooling of the DH water on an annual basis.

In Bøhm and Larsen (2004) the effect of DSM was investigated in the Roedovre DH system, connected to the VEKS transmission system in Copenhagen, and mainly supplying blocks of flats. Simulations showed that significant savings could be achieved by reducing the load variations in the buildings due to the incentive tariff between Roedovre DH company and VEKS.

Many single family houses in Denmark use a hot water tank for production of domestic hot water, although small heat exchangers are getting increasingly popular. The hot water tank will reduce the load on the DH system compared with a heat exchanger. Special storage tanks for buffering the DH heat have been investigated, Bøhm and Kjerulf-Jensen (1984), Lawaetz et al. (1986), sometimes in combination with solar heating systems, but they are not widely used today.

Lawaetz and Risager (1986) investigated the use of on/off control of the heating system in single family houses. By stopping the flow in the service line for 6 to 8 hours per day, the heat loss from the service line could be reduced by 6-20%. The space heating demand in the building was reduced by 2-10% by on/off control, the biggest savings found in light capacity buildings with large radiators. At the DH plant the energy savings were in the interval 2-8%.

#### 6.2. Heat Storage in Germany

#### 6.2.1. Heat Storage in Accumulators

In Germany most district heat producers operate heat accumulators. Since especially in the past a lot of district heating systems in Germany worked on a supply temperature level above 100 °C quite often pressurised storage systems are applied. The first heat storage was build at the end of the 60ies in Munich with a volume of 4650 m<sup>3</sup>. The heat accumulators work with pressures up to 32 bar. Beside the pressurised systems the number of unpressurised heat storage increases since more and more DH-companies managed to decrease the supply temperature to a level below 95 °C. The biggest German heat accumulator was built in Flensburg with a size of 30.000 m<sup>3</sup>. In average the storage size is approx. 9000 m<sup>3</sup> for pressurised and 10.500 m<sup>3</sup> for unpressurised accumulators.

The reasons for applying heat accumulators in Germany are more or less the same than in Denmark. They are operated

- to optimise production from large extraction CHP plants,
- to level daily heat load variations and avoid production in peak units,
- to level heat production variations of e.g. waste heat production,
- to serve as pressure maintenance of the system and as a water storage and
- to uncouple the heat and power production.

#### 6.2.2. Dynamic Heat Storage

Dynamic heat storage in the pipeline system of a district heating network is used quite often in Germany. Usually, it is applied on basis of heuristical information in order to lower e.g. the morning peak by increasing the supply temperature during night.

Winkins described that especially for bigger systems the heat storage in the pipeline system is of interest. In the district heating system of Mannheim the supply temperatures have been increased during night by 10 °C to 20 °C and decreased in the morning. By this strategy morning peaks of 70 MW to 140 MW could be shaved which lead to a stored energy of up to 400 MWh.

However, due to the lack of sophisticated software tools still heat storage in the pipeline system is not regarded as a strategy to improve the DH-systems efficiency.

#### 6.2.3. Demand Side Management

Within Germany a lot of strategies are followed with respect to a reduction of customers heat consumption by demand side management strategies. For example an optimised use and design of the hot water storage and optimised control devices like valves and pumps can be exemplary pointed out.

On the power sector there are also a couple of methods in discussion which are based on a automatic or controlled shut-down of electrical devices at the customer side. However, a temporarily controlled disconnection of specific customers is not applied in Germany.

#### 6.3. Heat Storage in Finland

#### 6.3.1. Heat Storage in Accumulators

Heat accumulators have been built since 1970's in Finland. These accumulators WERE unpressurised steel tanks with a volume of 10 000 - 20 000 m<sup>3</sup> and the thermal output varies between 50 - 130 MW. The tanks have a direct connection to DH-network. The largest heat storage is a rock cavern storage with a volume of 190000 m<sup>3</sup>. It was built in 1996. The heat storage is mainly connected to the system at the location of the CHP production plants. Connected to production units with a gas turbine a heat storage enables to drive the plants with full load and charge the heat storage during the day and shut down the plant at night while the heat storage supplies the DH-system. The reasons for using the heat storage are the same in Finland as mentioned above in Germany and Denmark. Additionally, in Finland the heat storage is used for planned and unplanned failures at the CHP and HOB production units. The summarised capacity of those tanks is 17500 MWh with a total volume of 350000 m<sup>3</sup>. They are charged/discharged in average 100 times a year. If the price difference between own electricity production in the CHP plants and NorldPool is in average 13 US\$/MWh and the difference of heat production by peat and heavy oil is 22 US\$/MWh and between natural gas and oil is 19 US\$/MWh, the estimated profit by using Finnish heat storage capacity would be about 44 million US\$ a year.

#### 6.3.2. Dynamic Heat Storage

Dynamic heat storage in the pipeline is used also in Finnish DH-systems. In Finland in most cases only the supply line is utilised as a heat storage. In the '90 the Finnish DH-companies were interviewed about the their appreciation towards heat storage into the pipeline system and more than half of the companies gave a positive answer. Based on that call-up the storage capacity of the Finnish DH supply pipelines can be evaluated to a total heat capacity of 1500 MWh. If a temperature lift of 15 °C is applied, a cumulative heat storage of 150 GWh can be gained per year. Corresponding to this figure the estimated profit could be about 3 million US\$ a year.

#### 6.3.3. Demand Side Management

DSM was discussed in 80'th in Finland and some rough experimental tests were carried out at VTT. In those days electronic equipment, also PC-machines, were expensive and clumsy. But those tests have proved that there is a sense using DSM for cutting peak loads in buildings. Nowadays there has be a technical turnover and economic ways exist to carry out DSM and utilise the automation systems which already exist in the buildings.

The research work executed in Finland during winter 2002-2003 showed that the maximum heat load of a massive building (body of concrete) can be temporarily (during 2-3 hours) reduced by a level of 20 - 25 % in average. In case studies the limit of room temperature was temporarily lowered up to 2 °C. If this kind of measures are performed in a large number of buildings simultaneously, the total load of a district heating network can be lowered up to 20 %. Additionally, it is even possible to control buildings which are separated in groups in a way that the DSM equipment successively lowers the respective building's temperatures in order to extend the duration of the peak cutting.

Based on the DSM experience in Jyväskylä a possible profit using DSM in whole building stock connected to the district heating system in Finland can be estimated. Based on a DSM utilisation in 50 % of the Finnish buildings (except industrial buildings), the estimated profit could be about 6.5 million US\$ a year.

# 7. Economic and Ecological Effects

#### 7.1. Cost Reductions due to Heat Storage in Heat Accumulators

A separated heat storage is normally a mineral wool insulated steel tank connected directly to the district heating system. The costs of heat storage consists of the tank and connection to the DH system. During the last years 15 steel tank heat storages have been built in Finland, most of them were connected to a CHP plant.

The costs for this heat storage can be described with the following equation. The corresponding storage costs are presented in

Figure 7-1. The costs do not include VAT.

$$H = 0.0462 \cdot V + 6.3819 \cdot \dot{Q}_{max} + 12.452$$
(25)

where V is the volume  $[m^3]$  and  $Q_{max}$  is the maximum thermal output [MW] of the heat storage. The volume and heat effect can be chosen independent of each other in the respective equation. The volume and maximum output energy are supposed to be connected together with the lilac line as a function of storage volume.



Figure 7-1. Steel tank heat storage cost as a function of volume and effect (kEUR = 1.306 US\$).

Model calculations have been carried out in order to evaluate the economic effect within the Jyväskylä system if a heat storage with a volume of 7000 m<sup>3</sup> is used to substitute the current oil tank. These calculations are based on 120 charging/discharging periods a year, what means about twice a week with an average charging/discharging period is 36 hours.

A heat accumulator of that size leads to a increasing heat production in Rauhanlahti CHP plant of about 6580 MWh/a (0.75 %). Parallel the electricity production raises by approximately 4110 MWh/a (0.91%). The heat storage with the thermal capacity of 25 MW can almost substitute the oil fired HOB in Savela. It has been evaluated that the profit will be maximised by selling electricity and changing the heat production on basis of oil to a peat fired heat production through the heat storage. The oil consumption decreases more than 5160 MWh (450 t) a year. Regarding the reduction on fuel demand 235000 US\$/a could be saved in production cost. If the expected useful life of the heat storage is assumed to be 20 years within this period about 1.1 Million US\$ (interest 5 %, 20a) investment could be obtained based on the annuity method. The procurement price of the mineral wool insulated and DH-system connected steel tank of 7000 m<sup>3</sup> with thermal effect of 25 MW is approx. 650000 US\$.

#### 7.2. Cost Reductions due to DHS

Heat storing into the pipeline system does not require necessarily any extra investment. It is only a new way to operating the DH-network by elevating the supply temperature of the production units by 10 - 20 °C during 2 - 3 hours. In most cases only the supply line is utilised as a heat storage. If bypasses exist in the network also the return line can be applied as a heat storage. In this case the lower design temperature in return pipelines has to be regarded. In some DH-systems a few remote controlled valves might be needed, if the supply temperate front should be limited to certain district heating areas.

Model based calculations have been carried out in order to evaluate the effect of heat storage in the supply line of the Jyväskylä DH-system. In these calculations the heat storage process is initiated by over-heating the network with temperature lifts of 10 - 20 °C. The main target of these calculations was to shave the morning peak by heat storage in the pipeline system.

It has been determined that the maximum heat input for shaving of the morning peak is about 20 MW and in total 42.5 MWh can be stored in the network each morning. Based on data of the heat consumption within the year 2002 it could be determined that the total charged heat is then 5400 MWh for cutting the peak loads in the morning over a period of up to 4 hours. The total cost savings were about 100000 US\$ a year.

Within the EVO case it has been evaluated whether the uncoupling of heat and power production in a CHP could lead to financial and economic advantages. For this purpose additional power is produced during peak time and this power is sold to the market it has been assumed that an average price difference of 8.75 US\$ (EEX 2005) could be reached.

A storage process in the supply line of the network and another situation where heat is stored via bypasses in the return line have been evaluated. In the first case in average 23 MWh power could be produced by heat storage in the latter 41 MWh per day.

This additional power production at peak load times lead to possible savings of 31000 US\$ for the heat storage in the pipeline system and 55000 US\$ for the storage in the supply line and the return line.

#### 7.3. Cost Reductions due to DSM

The minimum investment to realise a simple autonomous (time and outdoor temperature guided) DSM control in a district heated building utilising it's automation system is around 780 US\$ in Finland. The hot tap water system of the building is not controlled. This most simple version of DSM control lowers the heating loads always when the outdoor temperature is below the temperature limit where peak DH capacity is normally needed (0 °C) but still well above the temperature, which is critical for the recovery of normal heating mode (-20 °C). When heating system is dimensioned very close to the actual need there is no possibility to use DSM measures during the highest demand of heating. This would endanger the comfort of indoor climate as there is not enough capacity to raise the indoor temperature after a DSM reduction. If the whole heating system should be oversized just because of DSM, the DSM investment would not be economically feasible.

The demand operated DSM is possible to be controlled either by TCP/IP protocol (via the internet) or by GSM-modem. As easy to operate and low cost DSM control technology is already available and it can be utilised to a large number of new and existing buildings the technological basis of DSM is solved. A GSM-modem may lead to the lowest investment cost (1200 US\$/building) but the operation cost gets higher than internet based as the number of DSM controls is large.

In the case of Jyväskylä city there is a district heating network with about 300 MW<sub>th</sub> of maximum peak load. It was assumed that there are so many customers connected to demand side management that the daily peak demand can be reduced 20 % when needed. From this basis it was assumed, how many starts of heat-only boilers could be avoided annually. Peak cut of 20 % in Jyväskylä means about 160 buildings such as Governmental Centre (20 000 m<sup>3</sup>) or 460 buildings like Pensioners Day Centre (7 000 m<sup>3</sup>).

Based on simulations how to use energy production capacity when DSM is utilised, the total saving is 17000 US\$/a in the Jyväskylä case. Share of saving in the start-ups and tails of HOB is

about 11000 US\$/a. Thus it gives an average saving of 107 US\$ for each one of 160 consumers. Thus a DSM investment of 1100 US\$ per consumer (5 %, 15 a) is allowed.

If we assume to save an investment of 20 MW HOB (2.35 Million US\$) because of DSM and we divide it to 20 years with 5 % interest, the additional saving will be 188000 US\$/a and in addition maintenance and other fixed costs. It amounts to about 1175 US\$/a per consumer in the Jyväskylä case.

In buildings having size of 20000 m<sup>3</sup> (heating load >500 kW) the investment should be as simple as possible and still be able to carry out DSM operations effectively. Pay-back time will be 15 - 20 years (5%) in Jyväskylä case. If we assume to compensate DSM investment (160 x 1175 US\$ = 188000 US\$) with boiler investment then the estimated pay-back time for the rest of DSM investment (1570 US\$ -1175 US\$ = 395 US\$) will be about 4 years. Appropriate measuring and data storing equipment is required in the registering of peak heating demand.

#### 7.4. Ecological Effects of DHS

When district heating pipeline is used as heat storage in Jyväskylä the maximum heat cut was 20 MW (6.7 % of the annual maximum load). The loaded energy through the pipeline was 5400 MWh/a. It means saved amount 5824 MWh/a (510 t/a) of oil and inreased consumption 6220 MWh/a (2220 t/a) of peat. The total CO<sub>2</sub> emission increased 741 t/a.

When using separated heat storage tank in Jyväskylä heat production in Rauhanlahti CHP plant increases about 6580 MWh/a (0.75 %) and electricity about 4113 MWh/a (0.91%). The extra electricity production was sold to open electricity market. Heat only boilers load decreased about 5530 MWh/a. The amount of heat driven through the heat storage was about 35 000 MWh/a and maximum peak cut was 25 MW (8.3 % of the annual maximum load). The total consumption of peat increased 10 847 MWh/a (3970 tn/a) and heavy fuel oil decreased 5156 MWh/a (452 t/a). The total CO<sub>2</sub> emission increased 2670 t/a.

Within the EVO system the model based calculations have shown that it is possible to decrease the fuel consumption and the CO2-Emissions by approximately 10 to 15 % per MWh power produced on the basis of heat storage applications. This leads to a reduction of the fuel consumption of about 1250 MWh if only heat storage in the supply line is regarded and 2200 MWh if heat storage is applied to the supply and return line. The respective reductions of CO2 are 200 t/a and 600 t/a.

#### 7.5. Ecological Effects of DSM

When using DSM in Jyväskylä case the maximum heat load cut was 20 MW (6.7 % of the annual maximum load) in DH- system. The peak cut could be at maximum 60 % in the individual buildings. Savela boiler is peat fired, which was cut also. Saved amount of fuels were 35.6 MWh/a (3.1 t/a) heavy fuel oil and 197.1 MWh (70.2 t/a) peat. The emission reduction of CO<sub>2</sub> was 84 t/a.

# 8. Nomenclature

## Chapter 2

| GHWK           | Set of production units with backpressure turbines                 |
|----------------|--|
| GTHWK          | Set of production units with gasturbines                           |
| HW             | Set of production units with heat only boilers (HOB)               |
| К              | Weighting factor in objective function                             |
| SB             | Set of electricity nurchase contracts                              |
| WB             | Set of heat purchase contracts                                     |
| WD             | Set of neur purchase contracts                                     |
| Chapter 3      |  |
| А              | Area [m <sup>2</sup> ]   |
| С              | Thermal capacity [J/K]   |
| G              | thermal conductance [J/K]  |
| Р              | Power [W]  |
| Т              | Temperature [°C]   |
| U              | thermal transmission factor $(W/m^2K)$                             |
| c <sub>n</sub> | specific heat capacity (J/kgK)                                     |
| h              | Hight [m]  |
| q              | radiation to the surface (of a window) $[W/m^2]$ / Air flow [kg/s] |
| t              | time [s]   |
| θ              | Temperature difference [-]   |
| φ              | Thermal loss due to conduction [W]                                 |
| $\Psi_{sc}$    | Shadowfactor [-]   |
| α              | Factor for technical properties of the window [-]                  |
| n              | efficiency [-]   |
| 0              | density [kg/m <sup>3</sup> ]                                       |
| r<br>τ         | Time constant [s]  |
|                |  |
| С              | Cooling  |
| 0              | Outdoor  |
| IW             | Internal wall  |
| S              | Surface (internal)   |
| W              | Coat wall  |
| Win            | Window   |
| a              | air  |
| f              | Floor  |
| g              | Ground   |
| brs            | Heat recovery system   |
| i              | Internal   |
| r              | Radiation (of internal equipment)                                  |
| sol            | Solar  |
| vent           | Ventilation  |
|                |  |
| A(t)           | Dual control matrix for losses                                     |
| B(t)           | Dual control matrix for charging and discharging                   |
| D(t)           | Production matrix  |
| G(t)           | State matrix   |
| <u>\'</u>      |  |
| a(t)           | Costs vector due to storage of energy                              |
| b(t)           | Costs vector due to operational production                         |
| f(t)           | Vector units capacities and demands for heat and power             |
| p(t)           | Storage vector   |
| <b>d</b>       | Constant initial storage vector                                    |
| s(t)           | Inflow of energy   |
| - (-)          |  |

| u(t) | Optimal production vector |
|------|---------------------------|
| x(t) | State vector              |

## Chapter 5

| \dot{Q}_0           | Nominal heat load of a substation [W]                    |
|---------------------|--|
| Т                   | Temperature [°C]   |
| T <sub>R0</sub>     | Design return temperature of a substation [°C]           |
| T <sub>r,prim</sub> | primary return temperature of a substation [°C]          |
| T <sub>s,prim</sub> | primary supply temperature of a substation [°C]          |
| a                   | Constant [-]   |
| b                   | Constant [°C]  |
| t                   | time [s]   |
| $\sigma_{\rm L}$    | Dependency between heat load and return temperature [°C] |
| $\sigma_{\rm T}$    | Dependency between supply and return temperature [-]     |
|                     |  |

## Chapter 7

| Н               | Heat Storage Costs [kEUR]        |
|-----------------|----------------------------------|
| V               | Storage volume [m <sup>3</sup> ] |
| $\dot{Q}_{max}$ | Maximum thermal output [MW]      |

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# 10. Appendix

| BoFiT-ID | metering point | Q <sub>N</sub> [kW] | T <sub>V0</sub> [°C] | T <sub>R0</sub> [°C] | K <sub>Q</sub> [-] | K <sub>TV</sub> [-] |
|----------|----------------|---------------------|----------------------|----------------------|--------------------|---------------------|
| VB1154   | 20010105       | 997                 | 88.82                | 57.99                | 7.74               | 0.75                |
| VB0118   | 20010006       | 2009                | 80.07                | 42.87                | 1.00               | 1.00                |
| VB0169   | 26003117       | 1405                | 71.60                | 55.43                | 1.38               | -0.12               |
| VB1766   | 20010119       | 1906                | 81.80                | 61.80                | 1.25               | -2.09               |
| VB0199   | 20010047       | 2460                | 73.82                | 37.57                | 1.00               | 0.99                |
| VB0207   | 26003116       | 1693                | 78.48                | 57.54                | 1.22               | -0.30               |
| VB1733   | 26004654       | 1027                | 75.29                | 49.86                | 1.05               | 0.03                |
| VB0231   | 26005102       | 1693                | 77.93                | 57.72                | 0.99               | -0.13               |
| VB0238   | 20010015       | 1886                | 78.20                | 53.12                | 1.21               | -0.16               |
| VB0239   | 20010418       | 1921                | 74.98                | 54.55                | -8.07              | 0.00                |
| VB0278   | 26003114       | 1578                | 81.40                | 47.84                | 7.66               | 0.37                |
| VB1823   | 20010003       | 1110                | 78.78                | 45.52                | -14.34             | -0.17               |
| VB0633   | 26003118       | 3950                | 78.34                | 42.83                | 3.41               | 0.3                 |
| VB0745   | 26003702       | 3950                | 48.99                | 28.99                | 2.06               | 0.38                |
| VB2037   | 20010009       | 7118                | 80.69                | 50.99                | -12.40             | -0.66               |
| VB0349   | 20010017       | 7118                | 80.26                | 48.80                | 0.03               | 0.35                |
| VB0053   | 20010132       | 1853                | 77.39                | 57.39                | -9.42              | -1.15               |

### 10.1. Model Parameter of Customer Substations in Næstved

Table 10-1. Model Parameter of the measured Næstved customer substations





International Energy Agency IEA Implementing Agreement on District Heating and Cooling, including the integration of CHP

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